

Exploring the potential of biosolar roof development in urban environments: a look into Miami Beach, USA

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Abstract

Increased densification of cities has caused heightened competition for space. Given they are often unused, rooftops present a great opportunity for implementing sustainability solutions in dense urban environments. Biosolar roofs combine the benefits of green roofs and rooftop solar so that space can be used for multifunctional purposes more efficiently. Unfortunately, research remains limited for biosolar roofs in different climates and from an urban planning perspective. As a subtropical and coastal city, Miami Beach, USA presents a compelling study area to research the potential of biosolar roofs. In this thesis, a GIS analysis and policy analysis were performed to determine the potential of Miami Beach's roofscape for biosolar roof development considering various spatial criteria. The results of the GIS analysis demonstrate the application of a multi-criteria suitability analysis to prioritize the development of biosolar roofs in Miami Beach. The policy analysis reveals how feasible such a solution is to the study area via interviews and document analysis. By completing this interdisciplinary research study, this thesis adds an updated methodology for determining the potential of biosolar roofs in urban environments and provides specific recommendations for local officials based on location-specific results.

Acknowledgements

This thesis taught me a lot of skills in different software, the environmental research process, and time management. It is my hope that this work can be of help to researchers eager to learn more about biosolar roofs, Miami Beach officials and developers, and anybody else interested!

While it is an independent project on paper, there are so many people who have supported me throughout the entire thesis process that deserve recognition and acknowledgement.

Firstly, I would like to thank my family for their financial and emotional support throughout this process. I love them entirely and I would not have been able to accomplish much of the work I have done without them.

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Thirdly, there are also many individuals and resources that merit recognition for my completion of this thesis: my supervisor, Dr. Julia Camara de Assis, for her support in brainstorming, troubleshooting, editing, and more; all the professors and colleagues I worked with and learned from during and prior to my Master's program, as this project was a true combination of all my educational experiences; the Land Use Planning Chair group for allowing me to develop my own thesis project based on my personal interests; and, I believe it is important to recognize the positive and limited use of artificial intelligence (see section 3.4.3 for more information on how this was used responsibly).

Lastly, one of the things that kept me motivated throughout the thesis process was my music. At the same time as I was completing my thesis, I started to publish my own music on SoundCloud as Taev. I would appreciate it if you would give my music a listen and give my Taev profile a visit, as it was quite fun to make and it's something I am quite proud of.

Now...to the main aspiration for this thesis: *a greener, more sustainable Miami...*

This thesis is dedicated to my hometown.

Acronyms and abbreviations

Census – U.S. Census Bureau

FWS – United States Fish & Wildlife Service

GHG – Greenhouse Gas

GIS – Geographic information system (software)

GMCVB – Greater Miami Convention & Visitor's Bureau

GPM – Geographical Potential Model

GRQ – General research question

IPCC – Intergovernmental Panel on Climate Change

MDC – Miami-Dade County

MDPL – Miami Design Preservation League

NOAA – National Oceanic and Atmospheric Administration

SRQ – Sub-research question

TPL – The Trust for Public Land

UHI – Urban Heat Island

UNEP – United Nations Environmental Programme

USGS – United States Geological Survey

1. Introduction

For most of human history, most of the world's population resided in rural areas with cities only comprising a small portion of the total populace (Ritchie, et al., 2018). As cities expanded in size, so did the economic opportunities available for their citizens (Ritchie, et al., 2018). Due to this increase in opportunity, mostly as a result of rapid industrialization of numerous countries, urban population growth slowly overtook rural population growth until 2007 when, for the first time in recorded history, most humans resided in cities rather than in rural communities (Ritchie, et al., 2018). Unfortunately, an increased urban population has not translated to improved livability of urban areas with many cities struggling to keep up with rising population. In addition to the societal challenges faced by urban residents, urban development has fueled environmental destruction resulting in less natural areas within cities (Ramaiah & Avtar, 2019).

As a result of increased urbanization and densification of cities, competition for space has also increased (Ramaiah & Avtar, 2019). Some important challenges these dense urban environments face include lack of connected natural areas, increased energy demand, and higher heat stress (Deilami, et al., 2018; Lynch, 2018; Ramaiah & Avtar, 2019; Zhang, et al., 2019). The problem, however, remains how to most efficiently resolve these concerns with limited space availability.

1.1 Green spaces as urban environmental solutions

One of the ways that urbanization is adapting to mitigate its negative environmental impact is through the introduction of green spaces. An urban green space is an area in the urban environment with vegetation and other natural elements (Taylor & Hochuli, 2017). Fortunately, these spaces both tend to support more environmentally friendly spaces and ensure more livable areas for its residents (Röbbel, 2016).

Some of the most prominent benefits of green spaces to humans include: reduced stress and improved overall mental health, increased physical activity, and heightened child development (Aerts, et al., 2018). In addition to the direct health benefits observed, green spaces also contain numerous indirect health benefits from improved environmental quality.

Reduced air pollution due to the plant diversity found in green spaces highlights one of these benefits. As a result of better air quality, residents see a reduction in respiratory illnesses exacerbated by air pollution such as asthma (Aerts, et al., 2018).

Furthermore, well-planned green spaces can increase biodiversity of a region which urbanization traditionally threatens (Aerts, et al., 2018; Hu & Lima, 2024). As a result of improved biodiversity, wildlife populations are provided refuges while residents enjoy closer contact with nature resulting in improved quality of life (Dearborn & Kark, 2010; Keniger, et al., 2013).

Another such positive effect includes mitigation of the Urban Heat Island (UHI) Effect whereby cities' built infrastructure, mostly due to impervious and dark-colored surfaces, accumulates higher temperatures as compared to cities' non-urban surroundings (Deilami, et al., 2018). Green spaces ameliorate this by providing more shade and permeable surfaces (Deilami, et al., 2018). Through these shading effects, energy demand of nearby structures can also be reduced due to indirect cooling from greenery (Ramaiah & Avtar, 2019).

1.2 Rooftop sustainable development

While green space development is known to provide opportunities for sustainable urban development and greening projects, limited space remains a concern. One renowned solution for ameliorating this problem includes utilization of rooftop space for sustainable roof development. Remarkably, the urban roofscape already accounts for almost half of all impermeable areas of developed cities (Stovin, et al., 2012).

A sustainable roofing system is a roof adjustment which diminishes the UHI Effect, contributes to stormwater management practices, and/or decreases GHG emissions (City of Miami Beach, 2019). This often includes well-known practices like green roofs and solar roofs, and lesser-known installations like blue roofs, white roofs, and more. These systems range in complexity from painting surfaces white for higher reflectivity (white roof) to installing food-producing gardens on top of traditional roofs (one type of green roof).

Given the quantity of rooftop solutions available, selection of which roofing system to use presents an immediate obstacle. Interestingly, the synergy between solutions presents a compelling argument. Given the widely-studied nature of both green roofs and solar roofs separately, biosolar roofs (combined green-solar roofs) present the most appealing combined rooftop solution to resolve this concern (Talwar, et al., 2023).

1.3 Problem description

While green roofs and solar roofs, individually, are widely studied sustainable rooftop solutions, research for biosolar roof development remains understudied. This is especially true for research in different climatic conditions (Avitesh, 2020; Fleck, et al., 2022; Köhler, et al., 2002; Liao, et al., 2025; Shafique, et al., 2018; Talwar, et al., 2023). Furthermore, understanding the potential of the urban roofscape for sustainable rooftop solutions remains a challenge for cities (Slootweg, et al., 2023; Velázquez, et al., 2019). Therefore, the following gaps are of primary concern for this thesis:

1. There is limited knowledge on how to evaluate the potential of biosolar roofs for urban planning;
2. Existing research is highly geospatial context-dependent providing a lack of understanding for areas of different climates.

1.4 Research objective

The objective of this study is to inform strategies for the use of rooftops for sustainability solutions by investigating the potential contribution of biosolar roofs in increasing urban greenery and reducing energy demand.

1.4.1 Societal relevance

Urbanization demands that sustainability be a top priority in urban planning decisions. With increasingly limited space, rooftop solutions are becoming more popular (Mihalakakou, et al., 2023; Shafique, et al., 2018; Talwar, et al., 2023). This means that competition for rooftop solutions will increase and understanding which solutions best solve local concerns is important. By adding knowledge to biosolar roof research, this thesis will expand understanding for local city officials within the study area and beyond.

The study area of Miami Beach presents a particularly interesting study area since it is one of the world's top tourist destinations and, concurrently, it is situated in a unique subtropical ecoregion of the world: South Florida. It is also threatened by rising sea levels due to its increasingly warm climate and its location as one of Florida's barrier islands. With limited green space availability increasing densification due to population increase, there are many applications which could help both local Miami Beach officials and other cities with sustainability-related decision making. Using rooftop space for this purpose promotes exactly that, and understanding how to most effectively use Miami Beach's unused rooftop space for biosolar roofs is vital towards this concern as it is underexplored for the region.

1.4.2 Scientific relevance

While there already exists research conducted on green roofs (Bianchini & Hewage, 2012; Chow & Bakar, 2017; Francis & Jensen, 2017; Shafique, et al., 2018; Stovin, et al., 2012), solar roofs (Brown, et al., 2021; Lemay, et al., 2023), and biosolar roofs (Talwar, et al., 2023) there does not exist any conclusive methods for deciding when to implement either solution. The most relevant study examined green roof and solar roof selection, only, and concluded that selection between the two is limited by context (Dimond & Webb, 2017). As a result, this thesis will contribute to this growing body of research by examining the potential of a combined solution: biosolar roofs. This would also provide unique localized research to subtropical coastal cities like Miami Beach, with general applications to future studies in similar urban environments.

1.5 Thesis structure

The main text of the thesis is organized by the following chapters and key findings:

1. Introduction

This part of the report introduces the main topics of interest, problem statement, research objective, and the societal and scientific relevance of this study. This foundation is based on relevant literature important for understanding the main focus of this thesis.

2. Theoretical framework

Here, the theoretical underpinnings for green roofs, solar roofs, selection between both solutions, combination of both solutions (biosolar roofs), the concept of green connectivity, and the UHI Effect are described in detail. This information lays the groundwork for the entire thesis.

3. Methodology

This section is divided into three parts: study area, GIS analysis, and policy analysis. The first part describes the study area of Miami Beach and why this city is a compelling region for the problem of interest. The second part outlines the different analyses which make up the GIS analysis of this thesis. The detailed description of this section is found in the Appendix. The last part outlines how interviews and a document analysis were completed for the overall policy analysis.

4. Results

The results are presented in two parts: geospatial potential and policy feasibility of biosolar roof development. The first part presents the results of the GIS analysis with maps created in ArcGIS Pro and calculations completed using Python and Microsoft Excel. The second part presents results of the policy analysis with tables created from combined data from interviews and the online document analysis.

5. Discussion

The discussion provides further context on the results. Specifically, the results of the thesis are contextualized to the Miami Beach study area, compared internationally, and compared to scientific literature on biosolar roof research.

6. Conclusion

The concluding section of the main text of the thesis provides the main takeaways of the study based on the SRQs. This is followed by scientific and societal recommendations based on the findings of the research.

2. Theoretical framework

2.1 Green roofs

Green roofs are an ancient technique used for various purposes including insulation, gardening, and more (Shafique, et al., 2018). In this thesis, the definition provided by a 2018 review article is used whereby they are defined as “roofs planted with different kind of vegetation/plants on the top of growth medium” (Shafique, et al., 2018). They are a useful technique for making cities more livable and sustainable.

2.1.1 Benefits

The benefits of green roofs can be categorized by their environmental, social, and economic additions to a city. Environmentally, green roofs provide stormwater retention, reduce energy usage for buildings, support important ecosystem services and biodiversity in cities, and improve air quality (Mihalakakou, et al., 2023; Shafique, et al., 2018). Such projects can also connect existing green spaces to create ecologically sound green corridors along the city and improve the urban area’s interactions with nature. In consideration of the socio-economic factors of interest, energy cost reduction, noise reduction, aesthetic enhancement, and community building are of primary concern (Mihalakakou, et al., 2023; Shafique, et al., 2018). Green roofs have also been determined to be a low-risk investment while providing sound economic returns (Bianchini & Hewage, 2012). These features highlight the positive impact such eco-structures can have beyond their uniquely environmentally beneficial significance.

2.1.2 Challenges

While green roofs include multifaceted advantages for city sustainability, they do include certain challenges. Of these concerns, green roofs on buildings of lower heights usually provide stronger ecosystem services than taller buildings (Joshi & Teller, 2021), presenting a challenge to large cities with many skyscrapers. Height of buildings can also influence the impact green roofs have in cooling cities as proximity to ground level allows for more cooling for pedestrians than roofs of larger height (Joshi & Teller, 2021). In consideration of green roofs compared to conventional roof structures, moreover, the environmental impact can be approximately equivalent depending on the study referenced (Mihalakakou, et al., 2023). The main challenge, however, includes the lack of related research on the impact green roofs have on the urban environment (Joshi & Teller, 2021; Mihalakakou, et al., 2023; Shafique, et al., 2018).

2.1.3 Structural overview

The green roof system is a supplemental feature to existing building rooftops. This system consists of three main layers as outlined in Figure 1 (Mihalakakou, et al., 2023). The top layer (canopy layer) consists entirely of vegetation and is the most visible part of the roof influencing which cooling effects the system will primarily include based on plant species selection and climate (Mihalakakou, et al., 2023; Shafique, et al., 2018). The size of this layer depends on the type of green roof (see section 2.1.4). Underneath this layer, the soil layer includes the growth medium (soil) and plant roots for the vegetation above. This layer includes a complex mix of solid and liquid elements which significantly influence the green roof's growing capabilities (Mihalakakou, et al., 2023; Shafique, et al., 2018). The depth of this layer depends on the vegetation selected for use.

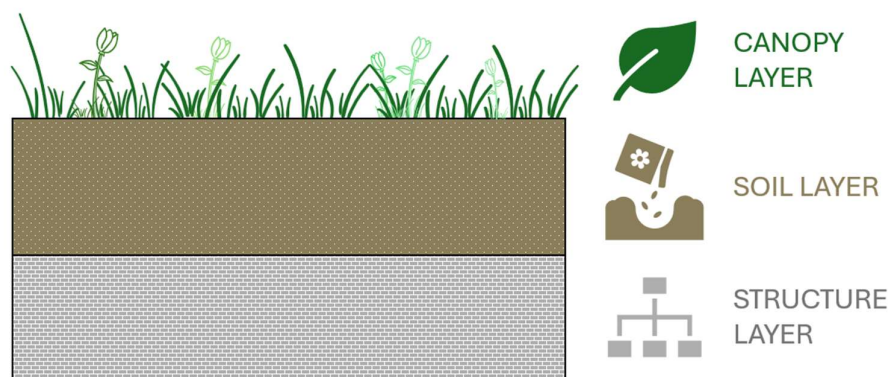


Figure 1. Simplified structural diagram of green roof system.

The final foundational layer (structure layer) is composed entirely of artificial material. This includes, in order from top to bottom, a filter membrane, a drainage layer, a waterproof membrane, a root barrier membrane, and finally the roof structure (Mihalakakou, et al., 2023; Shafique, et al., 2018). The filter membrane exists to distinguish the soil from the rest of the structure layer (Shafique, et al., 2018). The drainage layer allows excess water to be released from the soil (Shafique, et al., 2018), similar to the role of a pot for house plants. Finally, the waterproof and root barrier membranes protect the original roof structure from the green roof (Shafique, et al., 2018). An optional insulation layer can also be added before the drainage layer, but this would be unnecessary in a Miami Beach climate where seasons are not prevalent.

2.1.4 Types

There are broadly two main types of green roofs: intensive and extensive (Vijayaraghavan, 2016). The main feature separating the types of roofs from each other includes the depth of the soil layer and thus the vegetation each can host. Intensive green roofs can include a soil layer of up to 2 m deep with high investment and maintenance costs due to their heavy nature (Vijayaraghavan, 2016). Extensive green roofs, on the other hand, include a soil layer typically of 15 cm or less with low associated costs (Vijayaraghavan, 2016). There does also exist a category of semi-intensive green roofs which include a moderately thick soil layer between the two (Vijayaraghavan, 2016). Since most green roofs are extensive green roofs, however, this study will also focus on extensive green roofs only.

2.2 Solar roofs

In addition to solving urban greenery goals, cities can utilize rooftop space when ground space is limited in order to solve energy demand concerns. Solar roofs propose exactly that. Here, solar roofs, otherwise known as rooftop solar, are defined as the adoption of photovoltaic systems for electricity production on building rooftops (Lemay, et al., 2023). Given a change from fossil fuels to renewable energies is required for the sustainable energy transition, it is important to consider that the density of renewable energy plants (such as wind and solar farms) is lower than that of fossil fuels, thus requiring additional land to maintain the same amount of energy production (Lemay, et al., 2023).

2.2.1 Benefits

The main benefits of solar roofs are environmental and economic. Firstly, the production of renewable energy indirectly reduces the production of greenhouse gas emissions from nonrenewable energy sources (Brown, et al., 2021; Yang & Zou, 2015). This results in cleaner air and better health of urban residents. Economically, production of solar energy on building rooftops results in electricity bill savings for users and even surplus energy production which can be fed back into the city grid should one particularly sunny day produce a plentiful amount of electricity (Yang & Zou, 2015).

2.2.2 Challenges

While solar roofs are an impressive climate solution, there exists many related challenges which need to be addressed. Primarily, there is a significant injustice in adoption of the technology in residential areas as typically more affluent households will have greater access to the benefits due to affordability concerns (Konzen, et al., 2024). This inequity means residential adoption of solar solutions can often only be considered on a case-by-case basis, and still only for richer neighborhoods, usually. Furthermore, cost savings incurred from solar roofs are dependent on relevant policy to subsidize these efforts (Yang & Zou, 2015). Otherwise, payback periods may be too large for users to realistically consider investment. Additionally, high design costs for personalized solar roofs present a barrier toward their widespread adoption with each building hosting its own roof requirements (Yang & Zou, 2015). Lastly, solar roofs need to be located in areas of sufficient sunlight throughout the year so that they can effectively produce solar electricity (Hong, et al., 2017).

2.2.3 Technical overview

While it is not the focus of this thesis, it is important to consider the technical nature of solar roof solutions. It is the same technology used across all solar roof projects (photovoltaic solar panels); however, there are two main types of structures for their rooftop usage: (i) standard rooftop mounting structure and (ii) elevated solar panel structure (Gulalkari, et al., 2022). The first structure can be installed either as a railed system, a shared railed system, or a rail-less system (Gulalkari, et al., 2022). In each case a rail is either used to uphold a set of solar panels (railed), multiple solar panels (shared railed), or not at all (rail-less). Unlike green roofs, less modifications are needed to conventional roofs to support this technology, yet weight is still an important factor to consider on a case-by-case basis for buildings.

2.3 Green roofs vs. solar roofs

Given both green roofs and solar roofs provide environmental and social benefits to residents, scarcity of rooftop space demands proper selection of rooftop space utilization to ensure the most sustainable solutions are created. One 2017 study explored this dilemma through a 9-factor classification system of sustainability criteria and literature review (Dimond & Webb, 2017).

Unfortunately, this study proved that a reasonable comparison between these two rooftop systems was inconclusive and dependent on context (Dimond & Webb, 2017). Thus, as there remains no context-independent comparison method for determining whether to select green roofs or solar roofs, more research is needed on the subject. It is also important to note that biosolar roofs were not compared in this binary comparison study. Another study in the Netherlands compared the availability of rooftop space in Amsterdam for green roofs, solar roofs, and a mixed solution (Slootweg, et al., 2023). Here, the competition for rooftop space was found to occur predominantly in residential areas. Thus, the decision for which solution to adopt would be primarily based on residents' own preferences.

2.4 Biosolar roof development

Biosolar roofs, otherwise known as photovoltaic-green roofs, offer an approach to combine the benefits of green roofs and solar roofs. In fact, biosolar roofs have even been shown to increase photovoltaic efficiency while reducing ambient temperatures thus yielding an approach that is more powerful than traditional methods (Talwar, et al., 2023). Nevertheless, high investment costs and difficulties with implementation hinder this solution's widespread adoption (Shafique, et al., 2020). More research is also needed on the subject to better understand the specifics of combining both solutions in different geographical contexts (Talwar, et al., 2023).

2.4.1 Benefits

The specific benefits of using biosolar roofs incorporate components from green roofs and solar roofs. Firstly, it is important to understand why any alterations provide benefits compared to a traditional roof. In a nonmodified roof, sunlight is partially reflected and absorbed depending on the albedo of the roof material.

The greenery reduces the energy demand on the building providing for temperature-stabilizing effects, similar to green roofs (Talwar, et al., 2023). In large urban areas which capture a significant quantity of heat compared to their non-urban counterparts, such greenery can reduce the UHI Effect (Deilami, et al., 2018). This also helps reduce energy consumption for the buildings themselves, thus further providing economic benefits (Talwar, et al., 2023). Additional benefits of this greenery include capture of stormwater which reduces stress in the urban water drainage system (Shafique, et al., 2018; Talwar, et al., 2023).

When combined with photovoltaic panels, this type of green roof provides the same baseline benefits with more efficient solar panels than if they were standalone (Talwar, et al., 2023). This is because vegetation cleans the surface of photovoltaic panels by capturing dust particles (Nayak & Brar, 2020). On a broad scale, they can even statistically reduce air pollution in cities by as much as 2% (Dimond & Webb, 2017). The aesthetic appeal of greenery mixed with solar also proves to be more beneficial than only photovoltaic panels on a bare roof (Talwar, et al., 2023).

2.4.2 Challenges

While mostly beneficial, it is also important to consider local climate in the effectiveness of biosolar roofs given different solar irradiance, weather conditions, and plant species will all impact how a biosolar roof works as a technology (Talwar, et al., 2023). Hot and humid climates, in particular, require special attention due to the increased risk of disease transmission from mosquitos, for example (Köhler, et al., 2002). Addition of solar panels to the overall structure can also reduce stormwater retention benefits of conventional green roofs (Ciriminna, et al., 2019).

Similar to the challenges of solar roofs, moreover, and of general green infrastructure projects, introduction of biosolar roofs can induce gentrification which displaces original inhabitants of the region (Courtney, et al., 2021). For Miami Beach, where development projects are always underway, such a challenge would not present anything new, but rather could increase existing concerns.

2.4.3 Technical overview

Since a biosolar roof is a type of green roof, it contains the same base layer as green roofs with the addition of a “solar base” to add the photovoltaic panels as shown in Figure 2 (Ciriminna, et al., 2019). Since solar panels incur extra weight and investment costs, typically the greenery in biosolar roofs is composed of an extensive green roof instead of an intensive green roof (Fleck, et al., 2022). The most important features of the combined system includes the (i) photovoltaic panel height, (ii) the position of the photovoltaic panels relative to the green roof, and (iii) the proportion of photovoltaic panels to vegetation (Liao, et al., 2025). Each of these factors need to be designed specific to local climate conditions to ensure the most optimized system is created for solar and vegetation benefits (Liao, et al., 2025).

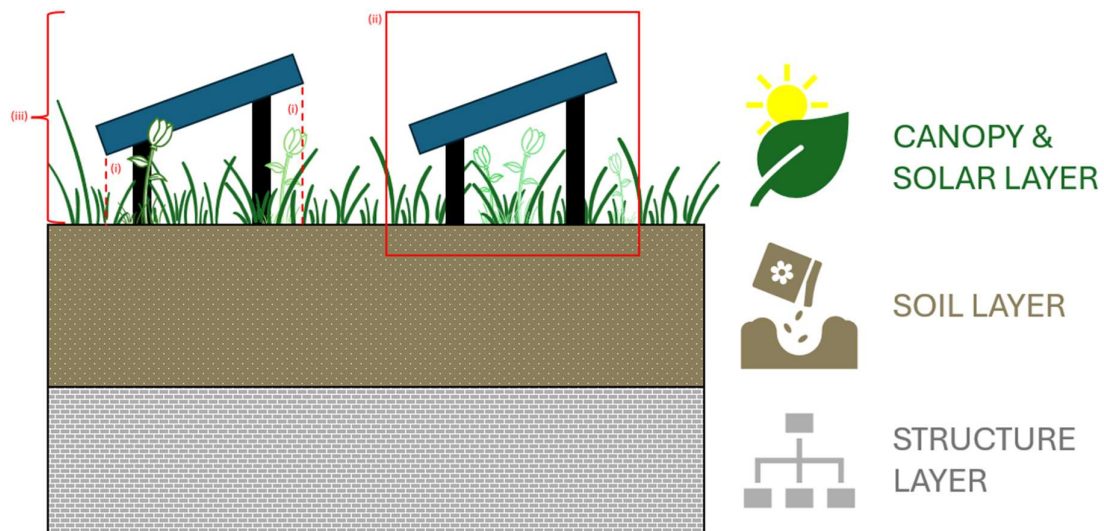


Figure 2. Simplified structural diagram of biosolar roof system. (i): height of photovoltaic panels; (ii): position of photovoltaic panels relative to green roof; (iii): proportion of photovoltaic panels to vegetation.

2.5 Green connectivity

Green connectivity, or habitat connectivity, refers to the connecting of urban green spaces “by corridors, forming a network facilitating dispersal and movement” (Zhang, et al., 2019). This is extremely important given many of the benefits from green spaces originates from that which connectivity promotes: biodiversity (Lynch, 2018).

2.5.1 Benefits

The benefits of green connectivity are plentiful. One of the most prominent impacts includes increased species richness and biodiversity (Lynch, 2018). This is possible because connection between green spaces allows for easier passage of wildlife between areas causing ecosystems to support each other instead of working separately (Lynch, 2018; Zhang, et al., 2019). This is important because it allows natural habitats to co-inhabit urban landscapes with humans with positive side effects. Other such benefits include mitigation of the UHI Effect, stormwater management, improved air quality, and improved social cohesion (Zhang, et al., 2019).

2.5.2 Challenges

While green connectivity is ideal for green space development in cities, there are various challenges from the planning perspective (Haaland & Bosch, 2015):

- Lack of space availability
- Social inequities with spatial distribution of green spaces
- Residents’ perception of green space availability
- High cost of high-quality green spaces
- Institutional constraints

While biosolar roof development would solve the first constraint by using rooftop space for additional green spaces, all of the other challenges would similarly remain present.

2.5.3 Technical overview with biosolar roofs

The design of green corridors involves two main strategies: (1) green corridors and (2) stepping-stones (Lynch, 2018). Green corridors are “direct, linear connections between habitats” which “create structural connectivity” (Lynch, 2018). They involve various different design morphologies based on network efficiency (Zhang, et al., 2019). Stepping-stones, on the other hand, are “small islands of habitat that serve as refuges between larger habitat patches” (Lynch, 2018). While corridors more effectively support biodiversity, stepping-stones best support connectivity when corridors are not possible for whatever reason (Lynch, 2018). Introduction of biosolar roofs, if created at the appropriate height above ground level (Joshi & Teller, 2021), could support either solution for green connectivity between already-existing green spaces.

2.6 UHI Effect

The UHI Effect is a widely recognized phenomenon in which heat accumulates in urban centers causing elevated temperatures when compared to rural counterparts. This effect has been studied since the early 1800s when it was observed that the urban climate of London, England, experienced hotter temperatures than its non-urban surroundings (Yang, et al., 2016).

2.6.1 Influential factors

The most important factors responsible for this effect include (Deilami, et al., 2018):

- Land use patterns (including vegetation percentage, waterbody proportion, pavement area, etc.)
- Seasonal variation
- Urban size
- Day/night time variation
- Population

The most important UHI Effect factors for biosolar roof development include the thermal properties of building materials and availability of natural elements like vegetation and bodies of water (Deilami, et al., 2018). Thermal properties mostly include albedo (reflectance of materials) whereby higher values reflect more sunlight and absorb less thermal energy. This is how biosolar roofs can mitigate the effect.

2.6.2 Urban impact

While increased temperatures and heat stress are immediate impacts from this effect, the following factors also significantly impact the urban environment as a result of the effect:

- Increased precipitation events (Bornstein & Lin, 2000; Deilami, et al., 2018; Dixon & Mote, 2003)
- Increased energy demand (Deilami, et al., 2018; Santamouris, et al., 2015)
- Increased heat-related mortality (Deilami, et al., 2018; Hondula, et al., 2014; Mohajerani, et al., 2017)
- Decreased air quality (Mohajerani, et al., 2017)
- Decreased overall livability of city (Mohajerani, et al., 2017)

It is also important to note that these factors can be exacerbated during heatwaves whereby urban infrastructure lends way to more severe temperatures (Mohajerani, et al., 2017).

2.6.3 Mitigation strategies

Mitigation of the UHI Effect involves adjusting the parameters of the most influential factors. This primarily includes modifying thermal properties of building materials, implementing green city policy, and increasing urban ventilation and environmental management (Deilami, et al., 2018). Most green mitigation policy supports increasing vegetation cover and water-sensitive urban design (Deilami, et al., 2018).

Here, specific tactics like green roofs are particularly important because they can reduce the UHI Effect by increasing vegetation and thereby cooling areas of high heat stress (Shafique, et al., 2018). In fact, biosolar roofs can significantly reduce this effect due to cooling from greenery and reduced energy demand due to photovoltaic energy production (Talwar, et al., 2023). It is important, however, that greenery from roof adjustments is connected to existing green spaces to ensure the maximum benefits from vegetation cover is achieved (Deilami, et al., 2018).

2.7 Research questions

Based on the information presented, the general research question is as follows:

What is the *potential of biosolar roof development* in Miami Beach?

The sub-research questions (SRQs) are as follows:

1. To what extent does the Miami Beach *roofscape* support biosolar roof development generally?
2. To what extent would biosolar roof development contribute to urban greenery in Miami Beach?
3. To what extent would biosolar roof development reduce energy demand in Miami Beach?
4. To what extent does the Miami Beach *roofscape* support biosolar roof development in terms of green connectivity, solar energy output, and UHI mitigation?
5. To what extent does Miami Beach *policy* support biosolar roof development?

2.7.1 Operationalization of key terms

In this thesis, the potential of biosolar roof development was operationalized into “roofscape” and “policy”, demonstrating the physical potential of this solution (roofscape) and the implementation feasibility of the solution (policy) (Figure 3). The former is based on a GIS analysis which examines physical elements which make this solution possible (Slootweg, et al., 2023). From this analysis, the physical suitability of rooftops for biosolar roof development is determined based on parameters from the literature. The latter is based on a policy analysis which examines existing policy and other elements for which this solution is realistically possible; namely, this includes sustainable roof policy, related sustainability policy, and other rooftop adjustment considerations for biosolar roof development.

Following selection of suitable rooftops in the GIS analysis, the roofscape potential can be further divided into four categories based on: green connectivity, solar energy output, UHI mitigation, and combined maximized benefits. The first category bases roofscape potential on the main greenery benefit of biosolar roofs. The second category bases roofscape potential on the main solar benefit of biosolar roofs. The third category bases roofscape potential based on the main green-solar roof benefits of biosolar roofs. The last category bases the roofscape potential on consideration of all of these factors to maximize benefits of the solution.

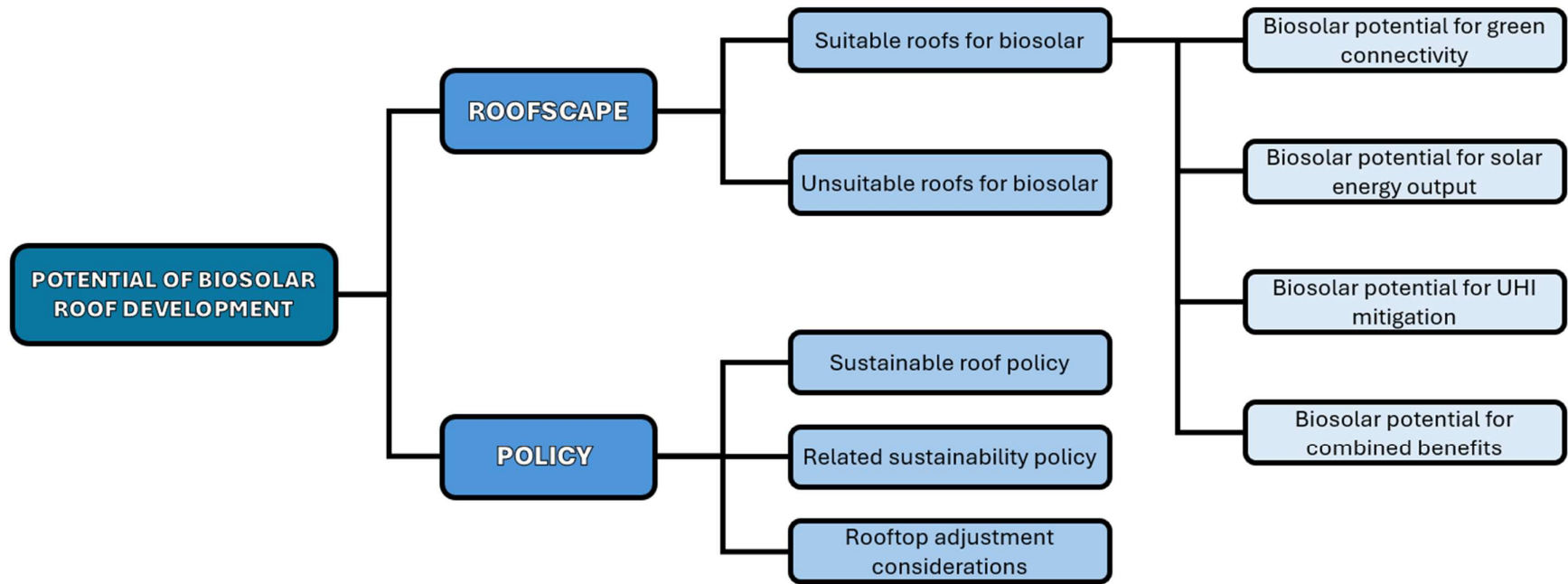


Figure 3. Tree diagram for operationalization of potential of biosolar roof development.

3. Methodology

3.1 Study area

Due to the lack of urban greenery and space for significantly more greenness in the City of Miami Beach (hereafter referred to as Miami Beach), it is important to find alternative ways to green the area beyond just parks and tree-lined roads. Green roofs present an opportunity to improve this problem. Nevertheless, unused rooftop space can also provide other sustainability benefits through solar roofs. As one of the top-20 sunniest cities in the United States (Douglas, 2023), and a prime city of the “Sunshine State” of Florida, Miami is a perfect location for solar energy despite less than 1% of its current energy usage originating from this mode of electricity production (GrindInfo, 2025). In fact, Florida is known as the state with the second-highest potential for electricity generation from rooftop solar within the United States (Lemay, et al., 2023). Thus, due to the above-mentioned environmental concerns, Miami Beach presents an ideal location for studying these concerns with applications to other subtropical, coastal, island, and/or multicultural city environments.

3.1.1 South Florida

South Florida contains a distinctive subtropical ecosystem with flora and fauna that cannot be found anywhere else in the continental United States (FWS, 1999). In addition to this unique environmental niche, it also contains the world-famous and culturally iconic Miami metropolitan area (hereafter referred synonymously with Miami) known as the “Gateway to the Americas” connecting Latin American influence with the United States (Maingot, 2014). This area includes the three southeasternmost counties in the Floridian peninsula (Figure 4).

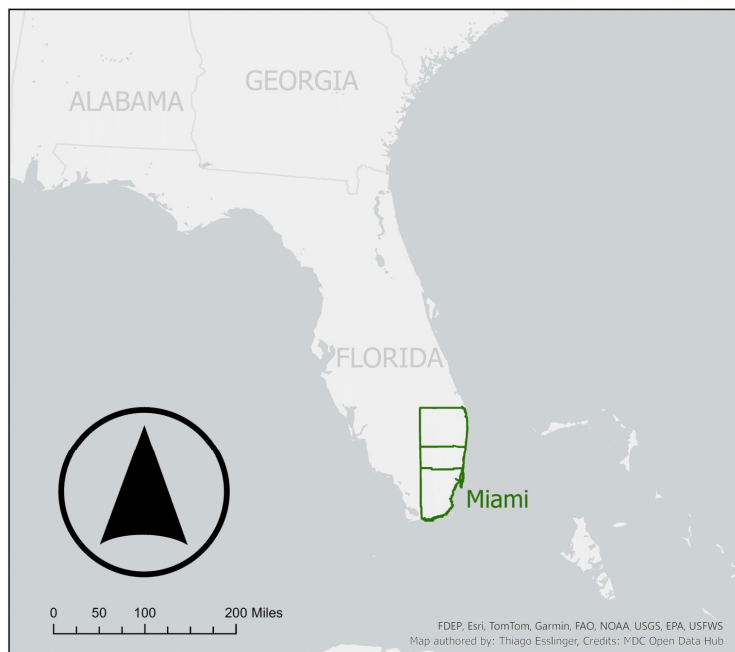


Figure 4. Map of Florida with the Miami metropolitan area highlighted in green.

3.1.2 Miami metropolitan area

Due to the attractive warm climate and impressive modern infrastructure, this metropolitan region is one of the fastest growing regions in the United States (Wilder & Mackun, 2024). However, rapid development is threatening the unique native habitat (WWF, n.d.). In order to prevent such environmental loss from increasing, Miami must find a way to integrate green spaces within its culturally rich urban area.

One proxy that has been previously used to explore the “greenness” of cities, of which green spaces would be abundant, is the urban tree canopy (Aditya & Ningam, 2021). Currently, MDC’s (the most populous county of the tri-county Miami metropolitan area) tree canopy constitutes 20.1% of the land use area which is notably less than the national urban American average of 28.8% and the recommendation of a minimum of 30% tree cover based on the 3-30-300 Rule (Croeser, et al., 2024; Dewald, et al., 2023; Konijnendijk, 2021). The 3-30-300 Rule states that sustainable urban planning should prioritize the following for each residential home: 3 trees visible, 30% tree canopy per neighborhood, and 300 m distance from the nearest park (Konijnendijk, 2021). With recent urban greenery initiatives, such as the decade-long Million Trees Miami project, failing to significantly increase this measure in MDC’s urban areas, green space availability remains limited (Dewald, et al., 2023). It is important to note, however, that initiatives like the Million Trees Miami project are still so new that differences in the tree canopy will take more time to be observed (Dewald, et al., 2023).

3.1.3 Miami Beach

Furthermore, inter-municipality differences within MDC remain important as there are 34 different municipalities with varying green space availability (MDC, 2024). Of these municipalities, Miami Beach is easily the most recognizable for its modern-day appeal and cultural significance (Figure 5). Unfortunately, Miami Beach includes an average tree canopy coverage of only 17%- worse than the average for the entire county (City of Miami Beach, 2020). The tree canopy coverage for parks in Miami Beach is noticeably larger at 28%, yet remains below the recommended 30% (City of Miami Beach, 2020). If all plantable areas in Miami Beach were utilized, the overall tree canopy potential would still only be 26.2% (City of Miami Beach, 2020). While this number is larger than the current statistic, it leaves Miami Beach less green than ideal.

Given the positive impact green spaces, especially parks (Terkenli, et al., 2017), can have on tourism (Cianga & Popescu, 2013), it is surprising that an international tourist hub like Miami Beach lacks such significant green space today and in its potential. In 2022 alone, the Greater Miami area received over 19 million overnight visitors who spent over \$20 billion (GMCVB, 2022). Thus, the added economic value of green spaces cannot be understated.

Furthermore, as a barrier island (Figure 5), Miami Beach is significantly impacted by seasonal tropical storms and hurricanes in addition to long-term climate change and rising sea levels. Such conditions make environmental planning extremely favorable to ensure the city’s longevity. Nevertheless, while there is significant knowledge about how supporting a greater urban tree canopy could positively impact stormwater management, rising temperatures, and overall livability of the city (City of Miami Beach, 2020), little research has been completed on underutilized roof space in this city.

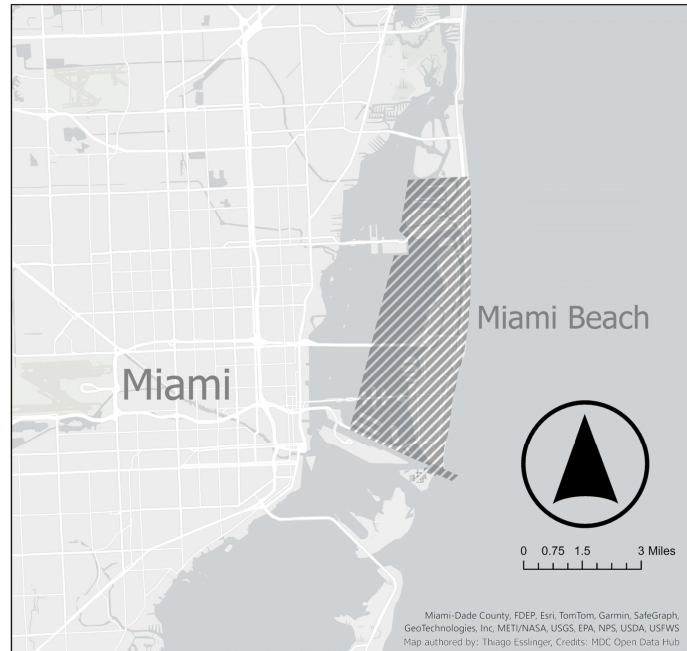


Figure 5. Map of Miami Beach municipal boundaries.

Thus, given the already-limited ground space available for urban greenery, such a situation presents an important local research gap. Furthermore, given the unused solar potential in the city and the possibility for other sustainable rooftop solutions such as solar roofs, Miami Beach proves to be an attractive study area for biosolar roof research.

3.2 GIS analysis of Miami Beach roofscape

In order to answer SRQ1, ArcGIS Pro was used as a mapping tool for determining the potential of the physical roofscape in Miami Beach. The method used was inspired heavily from a successful 2023 Dutch study whose methods determined the rooftop potential of Amsterdam for green roofs, photovoltaic panels, and the combination of both (Slootweg, et al., 2023).

3.2.1 Spatial dataset collection

To conduct a sufficient analysis on ArcGIS Pro, data for Miami Beach was collected from government websites. The MDC Information Technology Department was contacted for assistance in acquiring relevant data for this thesis project. Spatial data used included lidar, land use, municipal boundaries, and UHI severity (see Appendix A for more detailed information).

3.2.1.1 Lidar

Lidar (light detection and ranging, or LiDAR) technology has numerous applications to modern society. To gather data with this technology, a laser light is sent and reflected back to the receiver. The arrival time and change in wavelength of the laser light is then recorded to derive a 3D map, for example, of any region of interest (Neoge & Mehendale, 2020). Lidar data of buildings in Miami Beach was acquired from the NOAA Data Access Viewer using specifications outlined in Appendix A (NOAA, 2018). The most recent publicly available data from 2018 was used. Since this dataset was downloaded as multiple subsets, the Mosaic to New Raster tool was used to merge files with the parameters listed in Appendix B.

3.2.1.2 Land use and municipal boundaries

Land use data and municipal boundaries for Miami Beach were both acquired from the MDC Open Data Hub with parameters also outlined in Appendix A (MDC, 2024). The land use data was reclassified into simpler land use categories using Python according to Appendix C. The municipal boundary layer was used to define the boundaries of all datasets in this study as outlined in the Raster Cut tool usage in Appendix B.

3.2.1.3 UHI severity

Data for UHI severity in Miami Beach was acquired from an online ArcGIS Pro database by the Trust for Public Land (TPL, 2019). This data was collected over the summers of 2018 and 2019 for approximately 14,000 cities with a quality check of about 98.5% (TPL, 2019). Due to the large nature of the file, the Clip tool was used to crop the data for Miami Beach, only (see Appendix B).

3.2.2 Adjustment of roof parameters

Given Slootweg et al.'s methods were specific to the Netherlands and Dutch practices, it was necessary to adjust the roof parameters according to Miami Beach and American standards. This was done by contacting local roofing companies and reviewing the information from the literature review conducted by Slootweg et al. (2023).

3.2.2.1 Rooftop slope

Based on literature, the most appropriate rooftop slope in the Netherlands was determined to be 0-10° for biosolar roofs (Slootweg, et al., 2023). It is important to understand that the limiting factor for rooftop slope necessary for sustaining green roofs is building weight capacity (Breuning, 2025). Given this variable is independent of geographic context, the same values used for the Dutch study can be used here. The 0-10° slope value was also validated in interview with Jörg Breuning, Green Roof Technology founder (Breuning, 2025). Orientation of buildings was not considered because under 10°, it is not necessary for biosolar roofs (Slootweg, et al., 2023).

3.2.2.2 Rooftop space

Since green roofs and photovoltaics can be used in rooftops of any space, no restriction was placed on the shape of space considered for biosolar potential (Breuning, 2025; Slootweg, et al., 2023). However, since rooftops occasionally included obstructions which caused differences in slope of greater than 10° upon analysis in ArcGIS Pro, modelling only included rooftop spaces of 10 m² or more continuous space as “suitable” based on clustering done by Slootweg et al. (2023).

3.2.2.3 Rooftop load-bearing capacity omission

While load-bearing capacity is an important parameter for building rooftop additions (Breuning, 2025; Slootweg, et al., 2023), it has not been included in this thesis given it's a case-by-case selection and not feasible for a model of this scale (Slootweg, et al., 2023).

3.2.3 Modelling

In order to develop the correct geographical potential model (GPM) for this project, the GPM from Slootweg et al. (2023) used as a foundation with data from the MDC Open Data Hub. Following trial and error with various datasets and ArcGIS Pro tools, a new GPM was constructed for this thesis based on the most efficient methodology for the data available (Appendix B). Tools and datasets that were not necessary for the final product were not included in this report. A simplified GPM is demonstrated below (Figure 6). To simplify this process, a Python script was created to automate the entire GPM. This code was developed with the support of knowledge from the Wageningen University & Research “Programming in Python” course, general support from ChatGPT, and online forums.¹

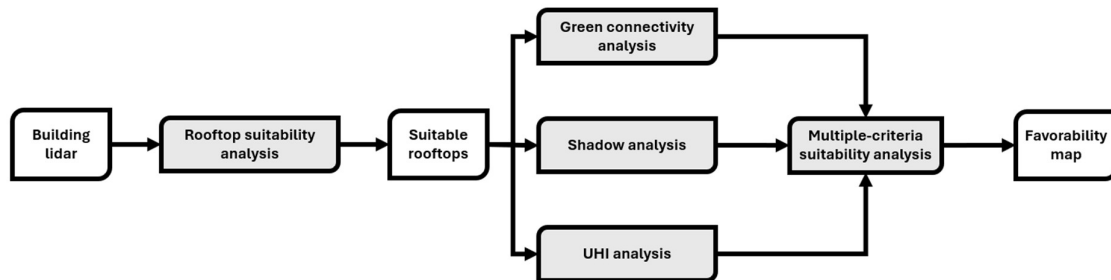


Figure 6. Flowchart of the GPM. Adapted from Figure C1 of Slootweg et al. (2023). Shaded shapes represent processes while unshaded shapes represent datasets. A detailed GPM for each analysis can be found in Appendix B.

3.2.3.1 Rooftop suitability analysis

As outlined in Figure 6, the building lidar mosaic acquired from NOAA was used as the main dataset for this research. Following this, the slope was determined for all rooftops and the slopes under 10° were selected. Here, the rooftop areas of at least 10 m² were selected from the roofs of interest. Once suitable rooftops were determined, three subsequent analyses were completed.

3.2.3.2 Green connectivity analysis

The green connectivity analysis was developed to determine how biosolar roofs could best support connectivity between existing green spaces in Miami Beach. Since proximity to green spaces is an important factor for green connectivity (Joshi & Teller, 2021), the lidar and land use datasets provide a great foundation for this analysis. First, green spaces were selected from the original land use dataset and a new layer was created from this selection (Appendix C) using the definition provided by MDC of green spaces as “natural areas, gardens, greens, squares, and plazas” (MDC, 2021). Other vegetation areas not found in green spaces, such as roadside trees, were disregarded in this definition due to data availability limitations.

Afterwards, this layer was converted into a raster, then a point dataset. In this format, it could be used as an input for the Kernel Density tool on ArcGIS Pro (Appendix B). A search radius of 300 m was selected so that this analysis would find suitable rooftops that would abide by the 3-30-300 Rule (Konijnendijk, 2021).

¹ Online forums referenced included the ESRI Community for Developers, Geeks for Geeks, Stack Overflow, numpy.org, pandas.pydata.org, and Finxter. All references are included in the original Python script available for public use alongside this thesis.

Once a kernel map was produced, it was mapped with “Natural Breaks” and classified on a 1-10 scale based on proximity to green spaces (1 = close, 10 = far). This was then intersected with the suitable rooftops dataset to find where potential biosolar roofs could increase connectivity of green spaces. While a more detailed map of all vegetation cover would yield more meaningful results, this data was not available. For a more detailed description, see Appendix B.

3.2.3.3 Shadow analysis

Given the importance of shade on the effectiveness and energy output of solar panels, a shadow analysis was also conducted for understanding the potential of biosolar roofs. Similar to Slootweg et al. (2023), the shadow analysis methodology followed Hong et al. (2017). Here, the altitude and azimuth of the sun were acquired based on latitude. This information was calculated using the Solar Position Calculator from NOAA for Miami, FL (Cornwall, et al., 2025) for every hour of sunlight (6am-8pm) on the 15th day of each month for 2018 (values are listed in Appendix D) (Hong, et al., 2017; Slootweg, et al., 2023). The hours of daylight were selected based on the earliest sunrise and latest sunset of the year for Miami Beach (Sunrise-Sunset, 2025). This input data of 144 data points (twilight hours were not considered) was then used for the Hillshade ArcGIS Pro tool (Hong, et al., 2017). The height of buildings was derived from the lidar input data.

Shaded areas (value of 0 from Hillshade results) were then selected and converted into a polygon using the Raster to Polygon tool with the same parameters as previous uses in this methodology (Appendix B). The 144 hour-month combination results (one result for each sunlight hour of one day per month) of the shadow analysis were then summed to create a shadow map of the entire region for all months of the year (ranging from 0 to 144 in which the lower value indicates less shading and the upper value indicates more shading throughout the year).

3.2.3.4 UHI analysis

To ensure a selection of rooftops for biosolar roof development that was comprehensive, consideration of the UHI Effect was also added to this methodology. For the UHI analysis, heat severity data from the USGS was used. The input data used was a raster file ranking severity from 1-5 (mild to severe). Since the data was collected from the 2018-19 season, it was compatible with the 2018 lidar dataset. This data was intersected with suitable rooftops to determine which rooftops could best mitigate this effect. Here, it is assumed that rooftops with a higher heat stress value would be more likely to benefit from the cooling effects of biosolar roofs (Talwar, et al., 2023). For more details on the GIS operation, see Appendix B.

3.2.3.5 Multiple-criteria suitability analysis

In order to complete a holistic analysis of where biosolar roofs would extract the most benefits within Miami Beach, the results from all previous analyses were combined to produce a favorability map. Building height was used as an additional consideration because biosolar roofs that are too tall may lose ecological connection with other green spaces (Joshi & Teller, 2021). The ideal building height was determined to be below 30 m as the tallest tree from the Miami Beach Urban Forestry Plan was the Cuban Royal Palm with a maximum height of 30 m tall (City of Miami Beach, 2020; Velázquez, et al., 2019). All factors considered were selected in order to maximize the benefits of biosolar roofs: connecting ecological corridors by constructing rooftop structures close to existing green spaces, higher energy production from more unshaded regions, and greater cooling effects for mitigating the UHI Effect in areas of high heat stress.

The Suitability Modeler tool on ArcGIS Pro was used for this combined analysis. The input rasters included the green connectivity kernel map, the shadow analysis map, and the UHI analysis map. Once input into the Suitability Modeler, the scales were transformed to a comparable scale (1-10) for each dataset (see Appendix B for more information). Each layer was weighed with a factor of 1; however, this could be adjusted depending on which biosolar roof benefit one wishes to optimize. In order to account for rooftop height for green connectivity, buildings with rooftops greater than 30 m were added as a “restricted location” in the Suitability Modeler tool, along with rooftops that were not already deemed suitable to ensure only suitable rooftops (based on rooftop slope and area) were considered for the final map. Favorability was then divided into low, moderate, and high based on equal intervals from the results of the Suitability Modeler.

3.2.4 Data analysis

3.2.4.1 Building analysis

In order to quantify the results by building, the datasets with (1) all rooftops and (2) with only suitable rooftops were converted into polygons and intersected with the Land Use dataset. From there, the total area in m² for each land use type was compiled into an Excel file where calculations were made to determine percent suitability by building (derived from land use type). Unfortunately, information on the age of buildings was not available for this study. Data was also cross-examined with Google Maps satellite imagery to verify large building uses, whenever necessary.

3.2.4.2 Greenery and solar output calculations

In order to answer SRQ2 and SRQ3, the following assumptions were made based on literature:

- Biosolar roofs contribute 0.7 m² greenery per square meter similar to green roofs (Brenneisen, 2004);
- Biosolar roofs contribute 1.2-5.3% more energy than traditional rooftops, according to literature from a similar climate (Abuseif & Gou, 2018);
- Average solar radiation for Miami Beach is 5.76 kWh/m²/day, according to the PVWatts Calculator from the National Renewable Energy Laboratory (NREL, 2025);
- Photovoltaic efficiency is 15% (Hong, et al., 2017).

Based on these assumptions, it was possible to calculate the impact biosolar roof development would have on overall greenery and energy consumption for Miami Beach. Using these assumptions, the following calculations were completed using the results of the rooftop suitability analysis:

Equation 1. Biosolar energy output. Based on Equation (13) from Hong et al. 2017.

$$Output = B \times \left(E \times \sum_{i=1}^{12} \left(\sum_{j=a}^p \left(A_{ij} \times \sum_{k=1}^n R_{ijk} \right) \right) \right)$$

In Equation 1, B represents the increased biosolar energy efficiency (1.2-5.3%), E represents photovoltaic efficiency (15%), A_{ij} represents the area of unshaded suitable rooftops at each given time from the shadow analysis, and R represents the assumed solar radiation for Miami Beach (5.76 kWh/m²/day). The result is given in kWh/day. From left to right: the variable in the first summation (i) represents the number of months in the year (12), the variable in the second summation (j) represents the number of daylight hours for Miami Beach in 24-hour format, and the variable in the last summation (k) represents the number of days in a month. The variables a and p are expressed like this because the number of daylight hours is dependent on the month and daylight savings time (a = first hour after sunrise, p = last hour before sunset). The variable n is also expressed like this because the number of days in a month is not consistent.

These results were then compared to totals to derive a percentage result. For greenery, this was divided by the total land area of Miami Beach (unchanged from 2018 to now). For solar energy production, this was divided by the total energy consumption for Miami Beach. Since this data was not readily publicly available, the total value was estimated by multiplying the energy consumption per capita for MDC (11.57MWh) (FindEnergy, 2025) by the population of Miami Beach in 2018 (91718) (Census, 2019).

Equation 2. Biosolar roof greenery output.

$$\Delta G = g \times A$$

Equation 3. Biosolar roof energy output.

$$\Delta E = e \times A$$

In both equations, the following is true: G represents overall greenery, g represents vegetation per square meter of suitable rooftops, A represents area of suitable rooftops, E represents energy production, and e represents the output from Equation 1. These results are presented in section 4.1.1 with rooftop suitability.

3.3 Policy analysis of Miami Beach sustainable roofing practices

To supplement the GIS analysis, a policy analysis was conducted simultaneously. This included interviews with local experts and a document analysis.

3.3.1 Interviews with local officials

The main purpose of conducting interviews with local officials was to supplement the document analysis in gathering information for the policy analysis.

The Chief Sustainability Officer of Miami Beach and other local contacts were contacted for interviews based on their qualifications as local government officials in Miami Beach. Interviewees were selected based on the convenience sampling methodology (Kumar, 2014). From this communication, three sustainability-related local professionals were selected for the study (see Table 1). Their names are not included for privacy purposes. These interviews were based on the unstructured narrative research methodology with a few guiding questions for interviewees to better understand the focus of the interview beforehand (see Appendix F) (Kumar, 2014). Interviews were recorded for transcripts to be derived. All interviewees consented to the recordings beforehand and, once the transcript was created, recordings were deleted.

Transcripts were reviewed manually and categorized using ATLAS.ti to produce structured results. This was completed using the open coding methodology described in the ATLAS.ti Workshop Booklet (Friese, 2019). Code groups were based on the SRQs of this thesis and sub-code groups were developed based on themes discussed during the interviews. Following analysis on ATLAS.ti, quotes were revised once more and general themes were derived as shown in Appendix F (Table 27, Table 28, Table 29).

Table 1. Interviews conducted.

#	Date	Length	Position
1	16 April 2025	40min.	Member of sustainability committee
2	24 April 2025	40min.	Member of sustainability committee
3	28 April 2025	45min.	Sustainability manager

3.3.2 Document analysis

The document analysis methodology was selected due to its time-efficient nature, availability of policy documents, and to strengthen the policy analysis overall (Bowen, 2009). The purpose of the document analysis is to answer SRQ5 regarding the policy landscape for Miami Beach’s roofscape and validate information discussed in the interviews. In order to complete this, a baseline assessment of the current local policies for the following was reviewed. The decision to focus on local (city and county only) policies was made due to time constraints, the importance that local policy plays on climate action (UNDP, 2025), and the current heightened uncertainty regarding federal and state policies making research at the federal and state level occasionally impossible due to lack of data. The following categories were of interest based on common green roof policies from across the globe (Talwar, et al., 2023):

- Solar incentives
- Green roof incentives
- Zoning regulations for rooftop adjustments
- Sustainability goals related to solar and/or green roofs

This was accomplished by searching through municipal and county government websites as outlined in Table 2. Key words included “green roof”, “rooftop solar”, “biosolar roof”, “vegetated roof”, “photovoltaic roof”, and “sustainable roof”. Results were compiled in a table with their sources. Specific policies discussed in the interviews were also examined further in this process.

Table 2. Websites searched for document analysis.

Type	Organization	Website
Municipal	City of Miami Beach	www.miamibeachfl.gov
County	MDC	www.miamidade.gov

3.4 Trustworthiness

3.4.1 Validity of methodology

The trustworthiness and validity of the results were of primary concern for this thesis. As a result, methodology was developed using peer-reviewed scientific literature, diverse datasets from reputable sources, and included personal checks of results to ensure precise completion of procedure was followed.

3.4.1.1 Credible foundation

Firstly, each analysis was founded upon a main research paper to ensure that the procedural steps completed during this thesis included a credible foundation. All additions and edits were recorded in detail either in the methodology or the appendix for reproducibility.

3.4.1.2 Diverse datasets

Secondly, various datasets were used to explore the potential of biosolar roof development in Miami Beach. For the GIS analysis, several decisions were made to support valid results. These included:

1. Acquisition of data from reliable databases including NOAA and the MDC Open Data Hub;
2. Most high-resolution lidar data parameters selected during acquisition (0.5 x 0.5 m);
3. Creation of Python script to remove unnecessary human error and improve reproducibility of analysis with new datasets as they are made available;
4. Interview with a green roof expert to validate rooftop parameters.

In addition to a quantitative GIS analysis, qualitative data was gathered from a short document analysis, and interviews with local officials. Such data acquisition ensures that the project results and conclusions are based on a broad overview of the area of interest and not solely on one source of information.

3.4.1.3 Strategic decisions

Lastly, various decisions were made in the methodology to ensure the most valid results were achieved. This includes the following:

1. Visual checks were performed after every procedural step, and errors were resolved along the way (this included confirming the first few Python-coded calculations via manual input on Microsoft Excel);
2. Calculations were performed to ensure no loss of data during polygon to raster data transformations throughout the methodology;
3. Overlap between the “road/street” land use type and buildings was discarded to avoid erroneous building classifications (see below for a more detailed explanation).

It is important to note, however, that due to limitations in data availability, especially for building classification, the percentage of suitable rooftops compared to total area and by building type were calculated in different ways. For total area, standard calculations were made with the lidar building mosaic data. For calculation by building type, a dataset with the overlap between building lidar data and roads removed was used. This is explained further in Figure 7.

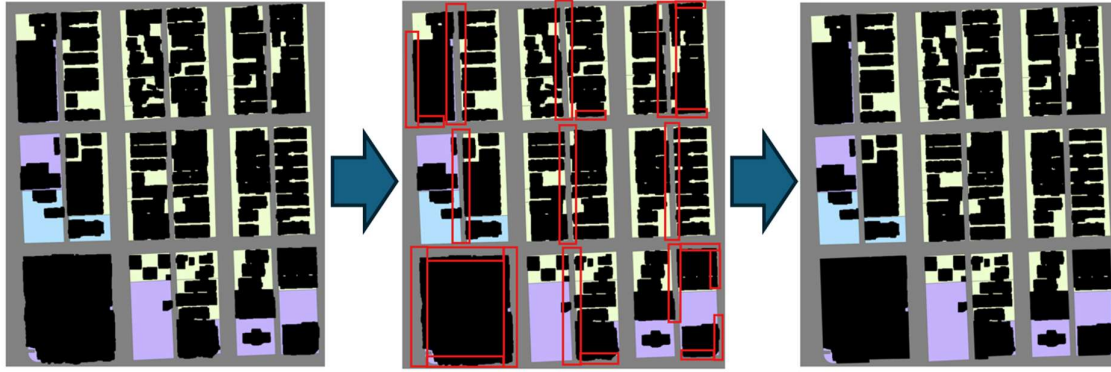


Figure 7. Building-land use type overlap concern. Left-most image: Lidar data in black overlayed on land use data in multicolor. The different colors indicate different land use types with gray indicating “road” feature. Middle image: Areas of overlap between buildings and road highlighted in red rectangles. Right-most image: Buildings in black after removal of data that overlapped with roads.

The concern presented in red rectangles in the middle image directly resulted in assignment of false building types by ArcGIS Pro. To ameliorate the problem, the overlap data was discarded as shown in the right-most image by assigning different values for road land use type and deleting the building parts that overlapped with this new land use type (see Python code in Appendix B). Interpolation between land use types over roads and Python script for road-building overlaps were both considered but not completed due to time constraints and other concerns. Notably, this would still not account for overlap of buildings over different land use data types in other regions (not only “Other”). Overall, the method selected resulted in a 4.6% increase in rooftop coverage for “Other” and 0.1% decrease in suitability overall. As a result, the difference should be sufficient for general purposes of this thesis and the percentage difference between overall calculations should be negligible.

3.4.1.4 Validation by experts

In order to ensure technical analyses were grounded on valid assumptions and following proper methodology, validation interviews with experts were planned and one was completed.

The validation interview was completed to increase the validity of the GIS analysis by gathering information for local green roof practices from a seasoned professional. Initially, 20 different American companies with expertise in solar and green roof solutions were contacted for an interview. Following this, an interview with the Green Roof Technology founder was completed in March over a WhatsApp call, and the results were used to finalize rooftop parameters in the GIS analysis (Breuning, 2025). Since this interview was conducted via the phone and its purpose constituted validation instead of data collection, a transcript was not collected.

3.4.2 Limitations of methodology

While significant effort was input to ensure a valid and successful study, there were limitations in the methodology that should be made clear for better understanding of the results.

3.4.2.1 Dataset availability limitations

The principal concern of interest included the availability of data for this project. While Miami hosts extensive publicly accessible GIS datasets for common use on the MDC Open Data Hub and via other governmental institutions like NOAA, the most recent data was only accessible as of 2018. Furthermore, the current political situation in the United States has resulted in understaffing at NOAA which, as per communication with NOAA in request of more recent data, has made public access to more recent data nearly impossible. In order to ameliorate this concern, a Python script was developed for Miami Beach officials to reuse the methodology of this research with more recent data, once it becomes available, with little hassle.

It is also important to note that despite the large repository of available datasets, there did not include detailed building information available for public use online. This resulted in the use of land use datasets to complete this research; however, there could be discrepancies between the land use dataset and the 2018 building lidar data used. This only affects the results by building type and for green spaces.

3.4.2.2 Analysis limitations

Given the nature of the GIS analysis is for city use, it is important to note that the analysis is only relevant from an urban perspective. This means that specifications regarding building structure and rooftop obstructions have been left to the consideration of architects and designers. As such, the results of this thesis should be used in consideration of this. It is also important to note that significant time was spent creating the GPM and refining the methodology with various trial-and-error runs. Due to this time constraint, further analyses were considered but not completed. They have been included in the Conclusion section.

There are also limitations on the green connectivity analysis and combined multiple-criteria suitability analysis. The former only considered green spaces, and not other vegetation across the city which could influence green connectivity in the urban landscape. Furthermore, the latter analysis considered green connectivity, shadow, heat stress, and building height, but other considerations could be important depending on the desired results (such as precipitation data for stormwater management purposes).

It is also important to note that datasets for existing green roofs and solar roofs were researched for this study; however, they were not taken into account. This should not be considered as a significant limitation due to: (1) the severe lack of sustainable rooftop adjustments in Miami Beach and (2) existing rooftop adjustments being out of scope of this study. Similarly, results relating to existing initiatives were not of relevance to this study when conducting the policy analysis. This thesis project aims to examine the potential of biosolar rooftop solutions for Miami Beach, and accordingly, any existing solutions would be additional information for the studied potential.

3.4.3 Ethics and AI management

3.4.3.1 *General ethical considerations*

Since the data used in this thesis originated from publicly available sources, there were no ethical concerns regarding the GIS analysis that required revision. For the policy analysis, consent was acquired from interviewees before collecting a transcript, yet names and job positions were removed from the final report to ensure that anonymity was safeguarded.

3.4.3.2 *Ethical use of artificial intelligence*

Artificial intelligence was used as a supplementary tool during this thesis. To ensure ethical compliance with artificial intelligence tools, moreover, the author of this thesis attended the “Responsible Generative AI Use For BSc/MSc Theses” workshop hosted by Wageningen University & Research on March 12th, 2025. The environmental impact of such tools was also considered during their use. As a result, the use of such tools was limited to two main uses only: (1) finding relevant resources and (2) providing technical support.

ChatGPT was initially used for testing different theoretical frameworks based on the author’s original ideas. Final decisions for structuring the theoretical framework, however, were made by the author based on data availability and a separate literature review. ChatGPT was also used for resolving technical issues with ArcGIS Pro when such support was not readily available via other online resources. Nevertheless, development of the complete methodology and execution of the GIS analysis were completed by the author.

Elicit AI was also used in a limited capacity. This tool was used for answering specific questions to more efficiently find relevant literature to understand new material. Use of this AI tool was useful in finding literature; however, more traditional methods for literature review provided more accurate and useful information for this thesis.

It should be noted that all ideas, final structuring decisions, development and execution of methodology, writing of the report, creation of figures, and the like, were completed entirely by the author of this thesis, and any information gathered from artificial intelligence was fact-checked by the author using Google Scholar. After using this tool, the author takes full responsibility for the content of this publication.

4. Results

The results of this research project were organized according to the methodology and similarly divided into two main sections for the GIS analysis and for the policy analysis.

4.1 Geospatial potential for biosolar roof development

4.1.1 Rooftop suitability based on rooftop parameters

Following completion of the GIS analysis for suitable rooftop area based on rooftop slope ($<10^\circ$) and rooftop area ($>10 \text{ m}^2$), approximately 63% of the total rooftop area in Miami Beach was found to be suitable based on these parameters. Based on Figure 8, it is clear that the most suitable areas are located mostly along the southside (between the areas below the Venetian Way entrance and above the MacArthur Causeway entrance) and the northside (above the JFK Causeway entrance) of the island with the center (near the Julia Tuttle Causeway entrance) of the island including many unsuitable roofs. It is also interesting to note that the Miami Beach Convention Center (the large building in Figure 8 adjacent to the road connecting Miami Beach with Venetian Way) stands out as mostly suitable for this technology based on these rooftop parameters, in addition to many buildings on the eastern coast of the city near the beach.

Based on the urban greenery and solar energy production calculations, it was also found that satisfying this biosolar roof potential would result in a 11% total land cover increase in greenery. This is more than a 50% increase in greenery as the current greenery land cover is 17% (City of Miami Beach, 2020). For energy, this potential could satisfy a 187-195% increase in current energy consumption by residents (1.99-2.07 TWh/year). This is a conservative estimate as it does not account for the added benefit of energy savings from biosolar roofs' cooling effects.

4.1.2 Rooftop suitability by building type

Upon further analysis, most (74%) of the suitable rooftop area proved to be from residential buildings (Figure 9; Figure 10). This was followed by commercial (15%), service and recreation (8%), other (3%), and industrial ($<1\%$) (Figure 10a). When examining percentage of suitable rooftops within each building type, the majority of rooftops for each building type proves to be suitable; the building type with the most proportionally suitable rooftops is "other" (72%) whereas the building type with the least proportionally suitable rooftops is "residential" (56%) (Figure 10b). Based on the distribution of rooftop area for the region, it is clear that there are mostly many small rooftops (especially residential) present throughout the city which are suitable for biosolar rooftop development (Figure 9; Figure 10c). There are a few notable exceptions: the Miami Beach Convention Center and adjacent buildings (mostly parking garages when cross-examined with Google Maps) (Figure 9).



Figure 8. Biosolar rooftop suitability in Miami Beach.

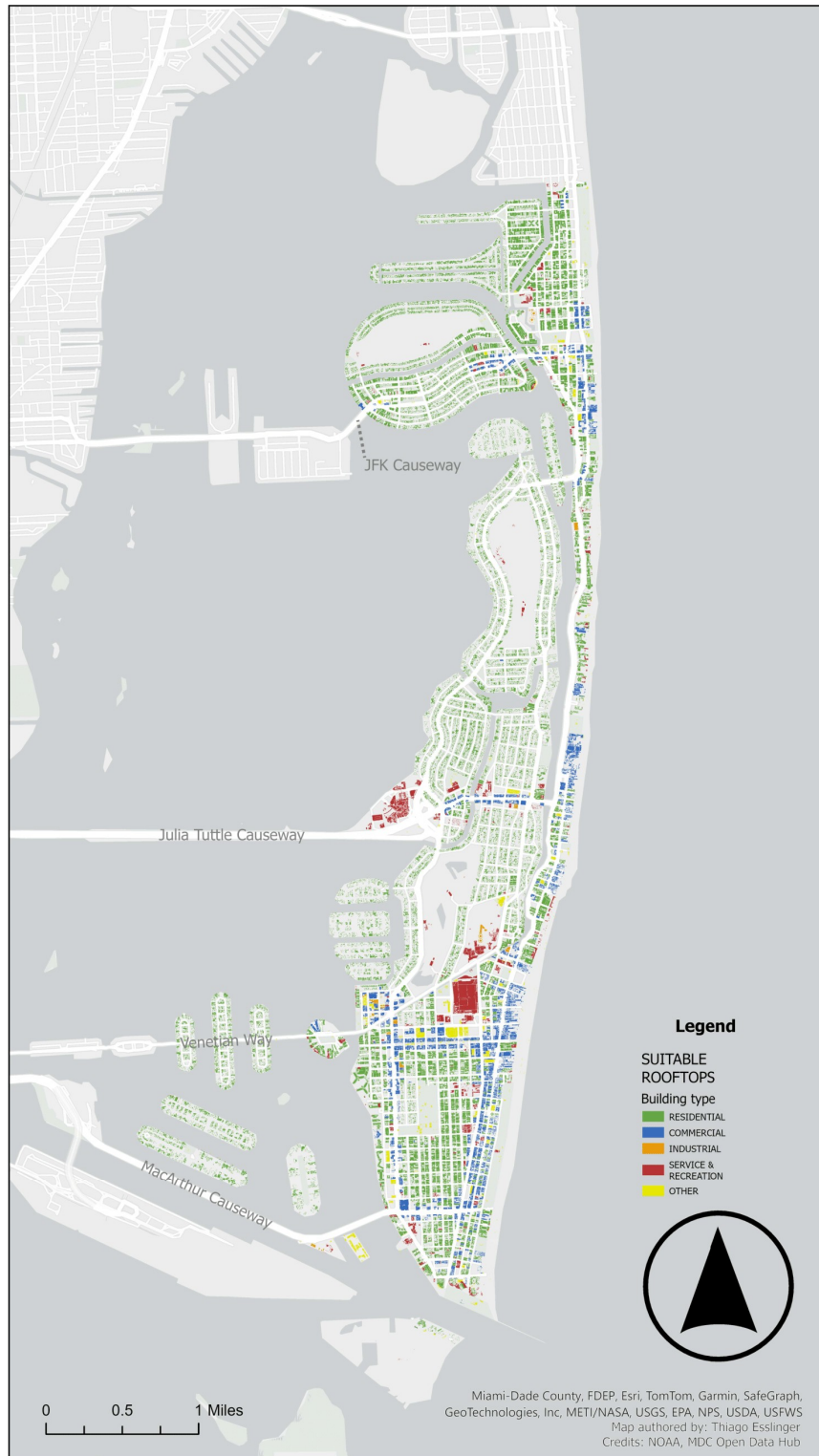


Figure 9. Biosolar rooftop suitability by building type in Miami Beach.

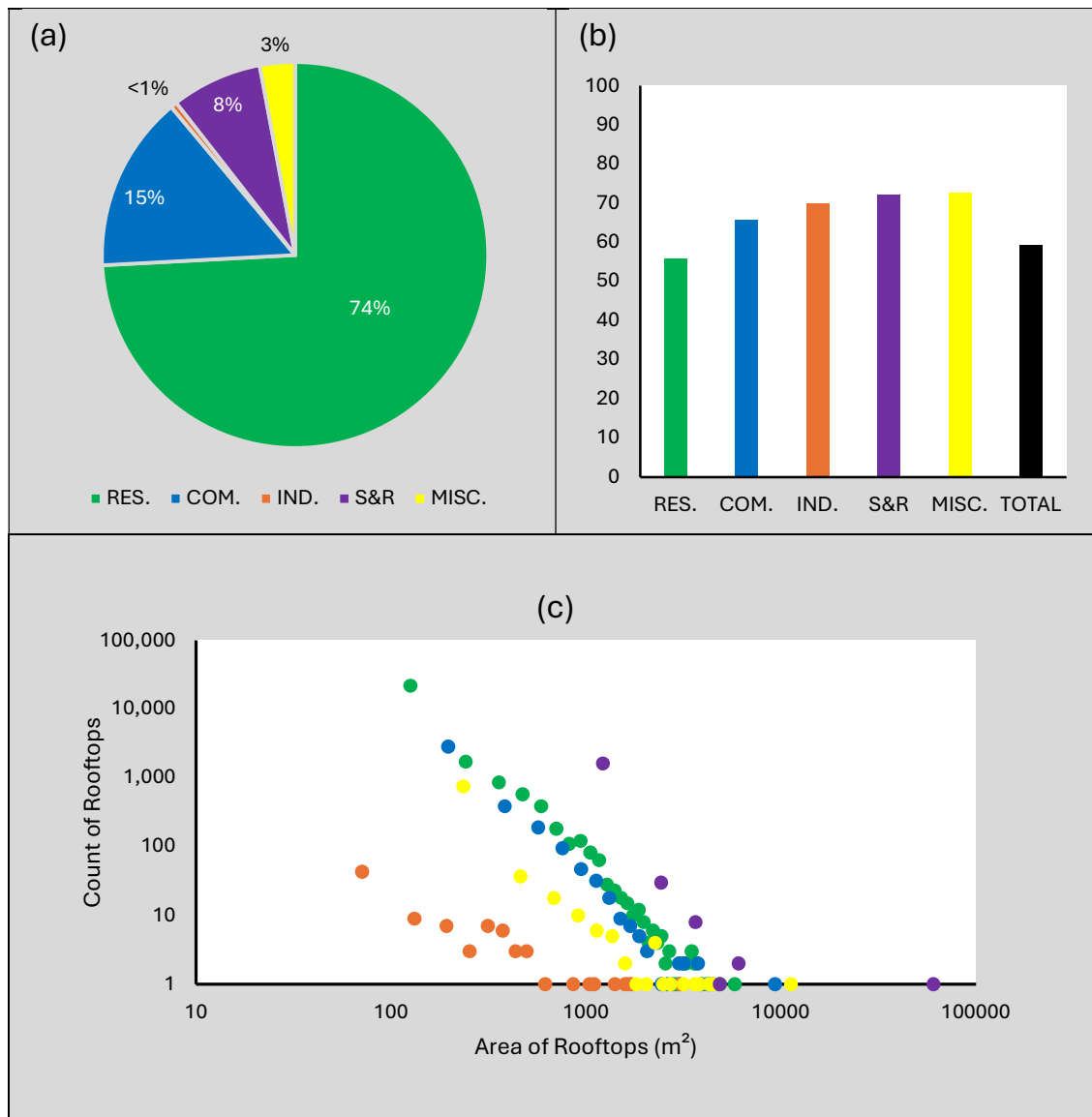


Figure 10. Building breakdown of biosolar potential availability. RES. = Residential, COM. = Commercial, IND. = Industrial, S&R = Service & Recreation, MISC. = Other building types. Part (a) demonstrates the percentage breakdown of building type for all the suitable rooftop area. Part (b) demonstrates the percentage breakdown of suitable rooftops from all rooftops for each individual building type. Part (c) demonstrates the distribution of rooftop area by building type. The y-axis shows the count of rooftops in a logarithmic scale while the x-axis shows the area of rooftops in square meters, also in a logarithmic scale.

4.1.3 Green connectivity analysis

Based on Figure 11, green spaces are spread throughout the city with the entire eastern side covered by natural space (notably: the beach). From Figure 12, it is clear that buildings surrounding green spaces towards the center (below the Julia Tuttle Causeway entrance and above the Venetian Way entrance) of the island are within a healthy distance to green spaces. However, it is notable that many buildings towards the south of the island, predominantly around the MacArthur Causeway entrance, in addition to many of the islands to the southwest of Miami Beach between Venetian Way and the MacArthur Causeway, are lacking green space nearby.



Figure 11. Green spaces in Miami Beach.

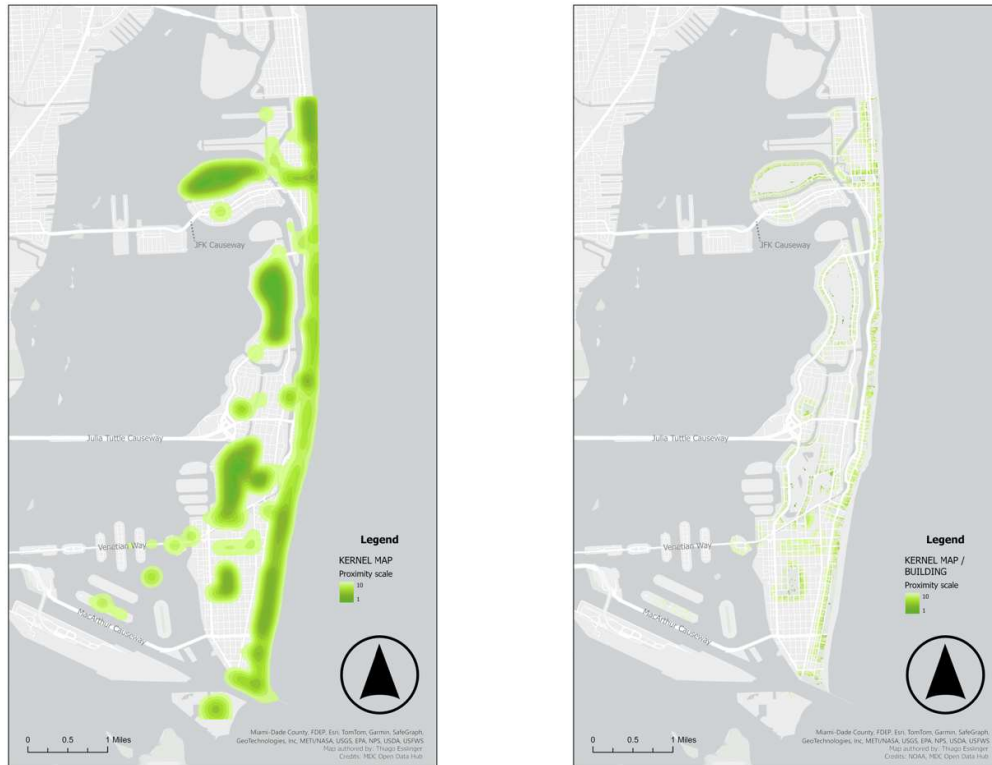


Figure 12. Kernel map of green spaces in Miami Beach. The left image shows Kernel map only. The right image shows the Kernel map overlaid with Figure 8.

4.1.4 Shadow analysis

The shadow analysis revealed which areas would be mostly shaded throughout the year. The sunniest moments occurred from 12:00-14:00 from April to August when at least 98% of suitable rooftops were unshaded (Table 26). Suitable rooftops were least shaded overall in January and December alike when the sun is least likely to appear. Specifically, the sunniest moments for January included 93% of suitable rooftops unshaded from 12:00-13:00 while in December this value was also 93% only at 12:00 (Table 26). The most shaded moments occurred in the morning hours of winter months (i.e. 4% unshaded at 7:00 on February 15th) (Table 26 in Appendix D).

Based on Figure 13, most of the shaded regions were secluded to the eastern coast and much of the southern island borders. Residential areas to the northwest proved to be the sunniest, especially near the JFK Causeway entrance. The islands to the southwest of Miami Beach between Venetian Way and the MacArthur Causeway also proved to be particularly sunny, whereas some notable areas in the center of the city, such as the Mount Sinai Medical Center (the first building near the Julia Tuttle Causeway entrance) and Belle Isle (the island closest to Miami Beach along Venetian Way), proved to be mostly shaded.



Figure 13. Shadow analysis for biosolar-suitable rooftops.

4.1.5 UHI analysis

The UHI Effect for Miami Beach was mostly concentrated on the southern side of the island where the main urban center is located (Figure 14). Approximately 10% of suitable rooftops experienced low to moderate heat stress, while less than 1% experienced high heat stress. While there were a few areas of heat stress toward the north, the UHI Effect does not seem to be a major problem for these neighborhoods. Notably, the Miami Beach Convention Center and Mt. Sinai Medical Center are also likely candidates for biosolar rooftop development to reduce the UHI Effect. Most of the other buildings with severe heat stress are located more inland.

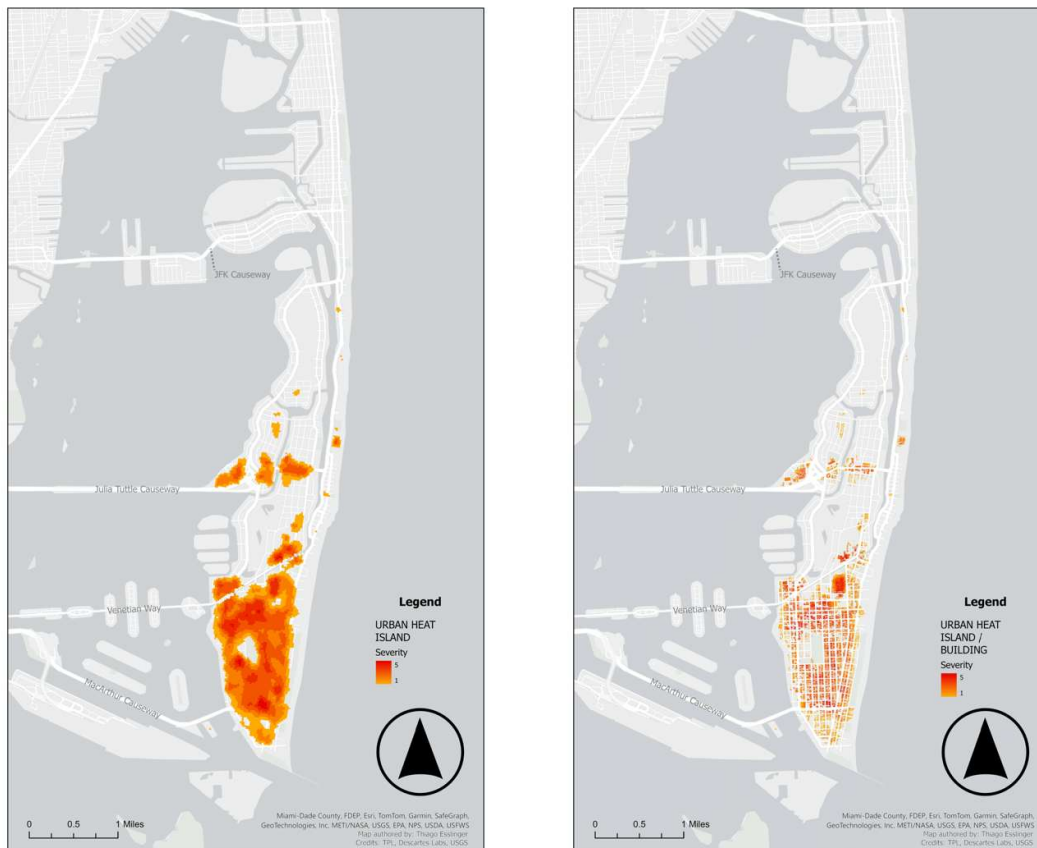


Figure 14. UHI Effect mapped onto Miami Beach. The left image shows the severity of the effect over Miami Beach while the right image shows the intersection of this image over suitable rooftops only.

4.1.6 Multiple-criteria suitability analysis

The results of this analysis can be summarized in a biosolar favorability map which combined all analyses and building height to examine which locations would produce the most benefits from biosolar roof development in Miami Beach. Based on Figure 15, it is clear that the southern half of Miami Beach, mostly away from the coast, proves to be the most favorable for this rooftop solution based on the combination of all analyses. Particularly, the Miami Beach Convention Center and many of the buildings to the south. Buildings towards the center of the island also prove moderately favorable for biosolar roof solutions, while buildings along the coast for the entire island prove less favorable. It is also clear that most suitable building rooftops exhibit either high (23%) or moderate (72%) favorability based on this combined analysis (Table 3).

Table 3. Favorability map percentages. Based on equal distribution of the range provided from the Suitability Modeler, the following percentages of all suitable rooftops were rated either low, moderate, or high.

Favorability	% of Total Area
Low	5
Moderate	72
High	23

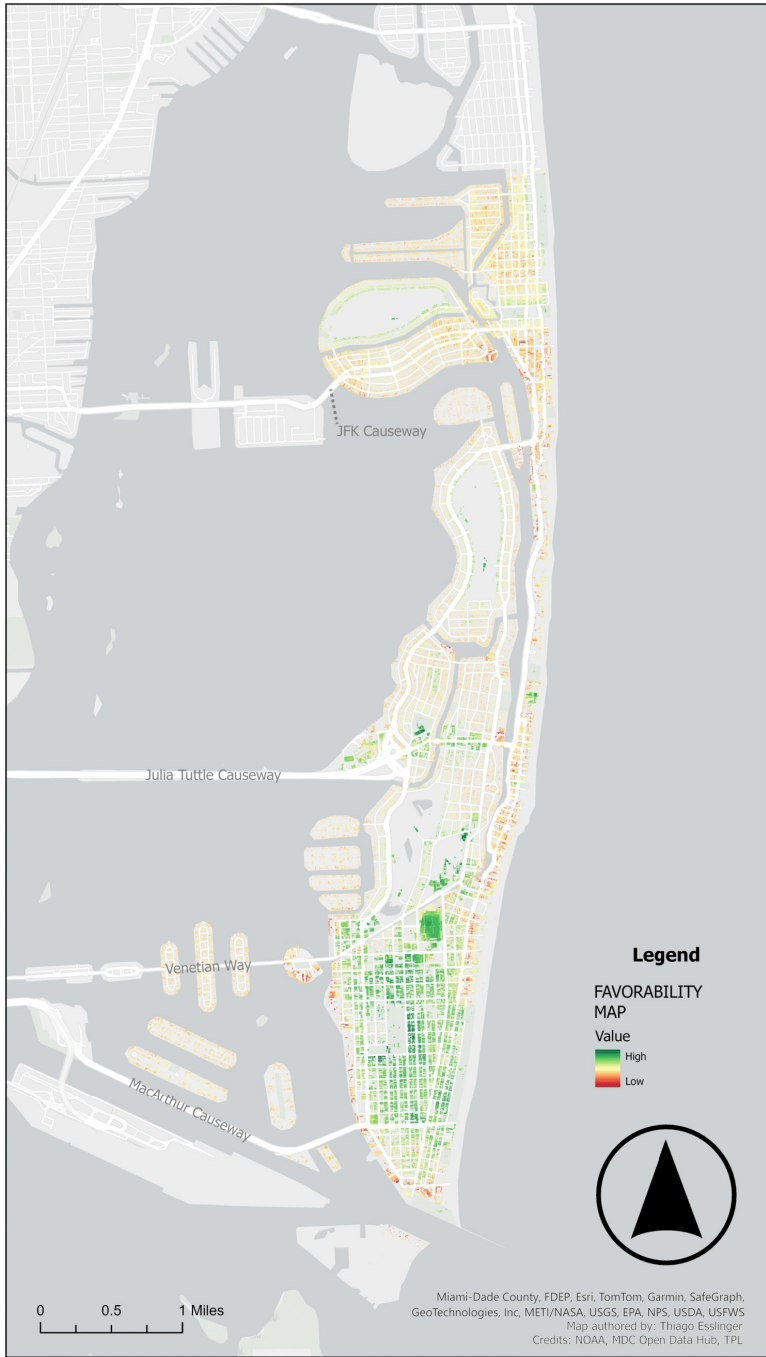


Figure 15. Favorability map for biosolar roof development based on the multiple-criteria suitability analysis.

4.2 Policy feasibility for biosolar roof development

4.2.1 Sustainable rooftop policy

Legislation for sustainable rooftop adjustments is commonplace in Miami Beach's political landscape. Primarily, there are two city ordinances which prove to be significant in advancing sustainable rooftops (Table 4). First, the Green Building Ordinance requires all new construction of a certain size to be certified as gold by LEED or certified by the Living Building Challenge. Since biosolar roofs contribute to energy efficiency, water efficiency, and overall sustainability of buildings, their addition would contribute to this ordinance. Second, the UHI Ordinance explicitly requires all new construction to adopt sustainable roofs, which would include biosolar roofs.

There are also various policies which could support the implementation of biosolar roofs in Miami Beach (Table 5). While Miami Beach has restrictions on building height, these are not inclusive of photovoltaic panels. Additionally, all fees related to the permitting process for these panels are waived by the government. There also exists other, federally funded, programs to finance solar panels for urban residents. Given that biosolar roofs are both green roofs and solar roofs, they could be considered under these benefits.

Table 4. Mandatory policy related to biosolar roof development.

Policy	Relevance	Date	Relevant information
Green Building Ordinance (Ordinance 2016-3993)²	Sustainable construction	2016	City of Miami Beach ordinance. <i>The following must be true for all new construction over 7000 sq. ft. or ground floor additions over 10000 sq. ft:</i> • LEED Gold-certified or; • Living Building Challenge-certified
UHI Ordinance (Ordinance 2019-4252)³	Sustainable roofs	2019	City of Miami Beach ordinance. <i>Any new construction must adopt a sustainable roofing system which will reduce the heat island effect including:</i> • Solar roofs • Blue roofs • Cool roofs • Green roofs • Other roofing systems

² <https://www.mbrisingabove.com/climate-adaptation/green-infrastructure/green-building-ordinance/>

³ <https://www.mbrisingabove.com/climate-adaptation/green-infrastructure/roofs/>

Table 5. Supportive policy for biosolar roof development.

Policy	Date	Relevant information
Resolution 2017-29872⁴	2017	City of Miami Beach resolution. <i>Public support by the city for Sierra Club’s “Ready for 100%” campaign.</i>
Ordinance 2017-4124⁵	2017	City of Miami Beach ordinance. <i>Allows height exceptions to buildings for sustainable roof systems including solar roofs, green roofs, and likely biosolar roofs.</i>
Ordinance 2017-4130⁶	2017	City of Miami Beach ordinance. <i>Waives “fees related to Land Use Board Approval” for photovoltaic installation on buildings.</i>
Ordinance 2017-4153⁷	2017	City of Miami Beach ordinance. <i>Waives all permit fees related to photovoltaic installation on buildings.</i>
Resolution 2018-30178⁸	2018	City of Miami Beach resolution. <i>Public support by the city for the purchasing of solar co-ops.</i>
SolSmart Gold designation (LTC-260-2019)⁹	2019	Federal distinction. <i>The City of Miami Beach was awarded this federal designation based on its steps to make solar “faster, cheaper, and easier”.</i>
Solar and Energy Loan Fund¹⁰	2021	Federal funding program (County-approved). <i>Assists residents’ payments for home improvements, including installing solar roofs, based on ability to pay rather than more traditional methods (credit score, equity).</i>
Inflation Reduction Act¹¹	2022	Federal legislation. <i>Provides tax credit of up to 30% of the cost for home improvements like rooftop solar.</i>
Property Assessed Clean Energy (PACE) Program¹²	2024	Federal funding program. <i>Allows property owners to pay for rooftop solar via loans repaid by property tax assessments for up to 20 years.</i>

4.2.2 Related sustainability policy

In addition to policy related to sustainable roofing practices, there are various sustainability policies which could support the implementation of biosolar roofs in Miami Beach (Table 6). The City Code for Tree Preservation ensures that existing vegetation across the city is protected. This means that any implementation of biosolar roofs for green connectivity purposes would not be impacted by artificial changes in vegetation within the city.

⁴ <https://www.mbrisingabove.com/wp-content/uploads/2018/07/2017-29872-Reso.pdf>

⁵ <https://www.mbrisingabove.com/wp-content/uploads/2018/07/2017-4124-Ordinance.pdf>

⁶ <https://www.mbrisingabove.com/wp-content/uploads/2018/07/2017-4130-Ordinance.pdf>

⁷ <https://www.mbrisingabove.com/wp-content/uploads/2018/07/2017-4153-Ordinance.pdf>

⁸ <https://www.mbrisingabove.com/wp-content/uploads/2018-30178-Reso.pdf>

⁹ <https://www.mbrisingabove.com/wp-content/uploads/LTC-260-2019.pdf>

¹⁰ <https://www.miamidade.gov/global/economy/resilience/energy.page>

¹¹ <https://www.irs.gov/inflation-reduction-act-of-2022>

¹² <https://floridapace.gov/about-pace/>

Furthermore, the 2040 Miami Beach Comprehensive Plan proves extremely relevant. Multiple policy recommendations from this document support the construction of green buildings and expansion of green spaces. Biosolar roofs are a combination of both of these desires.

Table 6. Related sustainability policy for biosolar roof development.

Policy	Date	Relevant information
City Code for Tree Preservation¹³	1998	Chapter of Code of the City of Miami Beach. <i>Establishes trees as an integral part of urban infrastructure and protects their status from haphazard removal.</i>
2040 Miami Beach Comprehensive Plan¹⁴	2019	Policy RSE 2.1.4. <i>“The City shall require that all proposed infrastructure and public facility improvement project address the feasibility of implementing a blue and green infrastructure component.”</i> Policy RSE 4.1.2. <i>“The City shall establish a green building program in the land development regulations that promotes the development of energy efficient green buildings, and that provides energy efficient green building thresholds for structures proposed for redevelopment.”</i> Policy HE 2.3.2. <i>“The City shall establish requirements for ‘green buildings’ through the Land Development Regulations. The Regulations shall include standards, including, but not limited to the following: a. Building permit applications for a green building project submitted or resubmitted for review shall be given priority review over projects that are not green building projects by the city’s departments reviewing such applications; b. All building inspections requested for green building projects shall be given priority over projects that are not green building projects; and c. Establishing minimum thresholds for mandatory ‘green building’ certification or providing for an alternative ‘sustainability fee program.’”</i> Policy HP 3.3.2. <i>“Establish Resiliency Districts based regulations that codify localized resiliency and adaptation strategies, including locating new green space co-benefit sites, local character preservation, historic resources preservation and design guidelines for adapting structures.”</i> Policy ROS 1.4.5. <i>“To ensure environmental sustainability, protection of natural areas and quality of urban life the city shall continue to protect publicly accessible urban greenspace and scenic open space vistas.”</i>

¹³ <https://www.miamibeachfl.gov/city-hall/environmental-sustainability/urban-forestry/city-code-for-tree-preservation/>

¹⁴ <https://www.mbrisingabove.com/wp-content/uploads/2040-Comprehensive-Plan-10-16-2019-Adopted-13MB.pdf>

4.2.3 Rooftop adjustment considerations

Results from the interviews and document analysis revealed various considerations biosolar roof development would require (Table 7). Aesthetics was a common consideration as biosolar roofs on historic and preserved buildings, for example, would require additional resources to increase sustainability while maintaining structural integrity. Furthermore, the unique architectural style of many of the historic buildings in Miami Beach include rooftops that are best left untouched. This is because rooftops are often integral features of select architectural styles and overlap between historically-protected and biosolar-suitable building rooftops presents a unique challenge. This can be seen in the map of historic districts and sites whereby a significant portion of the coastline and southern part of the island are demarcated “historic” (Figure 16). While this status requires additional considerations for any rooftop adjustment, the Art Deco-style frequently includes flat roofs and rooftop slopes across the city which cannot exceed 11% for a 5:1(horizontal : vertical) building. Thus, without the protected status, these buildings do appear quite ideal for biosolar roofs. However, these historic buildings are also important for protecting local identity.

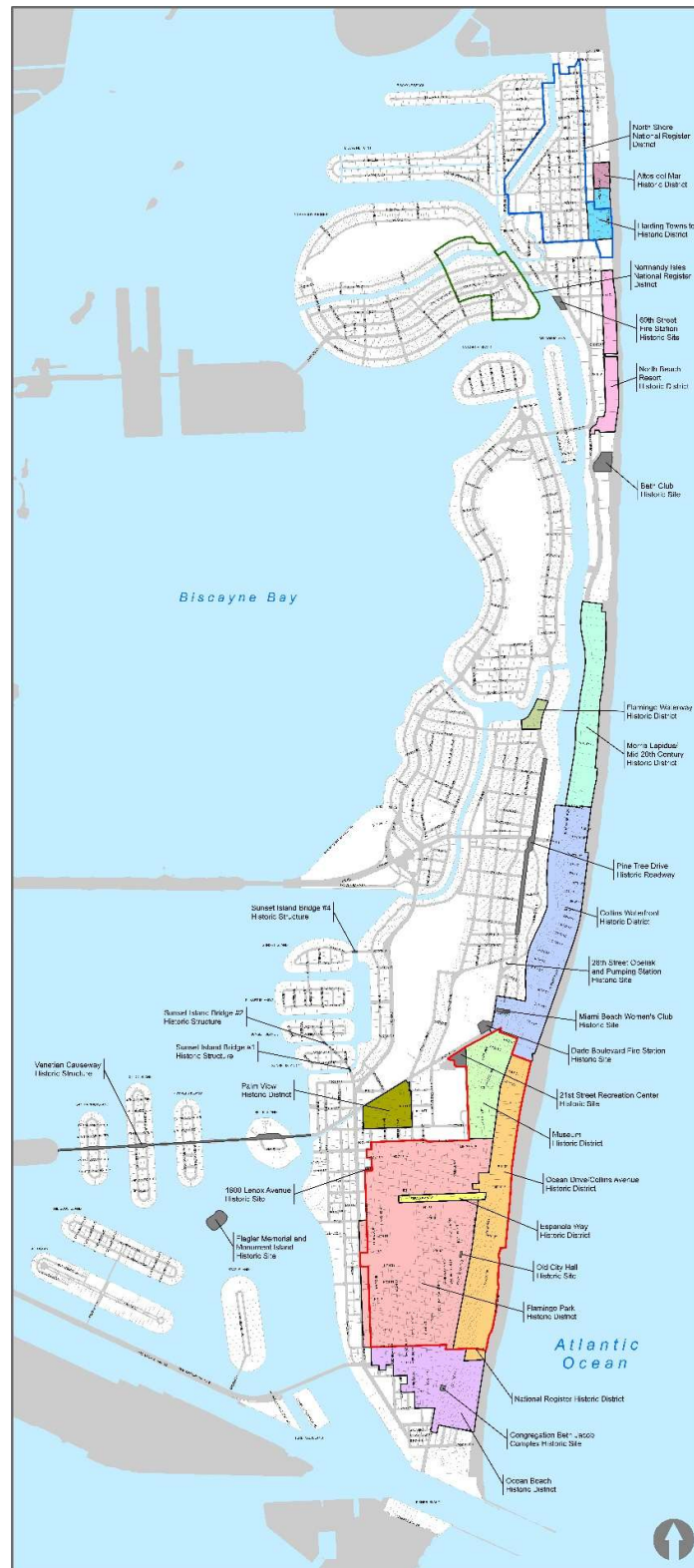
Table 7. Rooftop considerations for biosolar roof development.

Topic	Relevant information
Historic Preservation Board¹⁵	<i>Many buildings in Miami Beach hold a protected status due to efforts by this board.</i>
Rooftop architecture¹⁶	<i>The city hosts unique architectural styles whose key features include rooftop adjustments</i> • <i>Mediterranean Revival (“terracotta roof tiles”)</i> • <i>Art Deco (“decorative motifs”)</i> • <i>MiMo (“flat roof”)</i> • <i>Colonial Revival (“Gables roofs with dormer windows”)</i>
Rooftop permitting	<i>Permitting is part of the rooftop adjustment process, but requires significant time investment.</i>
Rooftop slopes ¹⁷	<i>Miami Beach Resiliency Code Chapter 7.1.2.3. Rooftop slopes must be less than 11%.</i>

¹⁵ <https://www.miamidade.gov/global/government/boards/historic-preservation.page>

¹⁶ <https://www.miamibeachfl.gov/architecture/>

¹⁷ <https://codehub.gridics.com/us/fl/miami-beach#/adb736bf-e704-4ba4-bd81-97c8b8b609fc/864665b5-7876-450e-9b6f-2ea8e2df50f1/5d08d584-f9db-4a46-bec1-ba6345639ec1/1fc14a56-8658-4db8-93e2-641be0006897>



MIAMI BEACH Historic Districts and Sites
 Prepared by the Planning Department, City of Miami Beach, 2009

Figure 16. Map of Historic Districts and Sites from online database (MDPL, 2009). All colored polygons represent historic districts.

5. Discussion

5.1 Biosolar rooftop suitability in Miami Beach

Rooftop suitability in Miami Beach for biosolar roof development proves to be promising on paper. With the majority of existing building roofs fitting the suitable rooftop parameters, the southern portion of the island city proves to be most suitable to resolve green connectivity, solar energy production, and UHI mitigation concerns. It is interesting to note that most suitable rooftops are residential. This puts most of the onus on residents to drive biosolar roof development; however, policy incentives do exist to support this implementation. It is also interesting to note how local architecture also influences the feasibility of implementing this solution.

The Art Deco flat-roof style is predominant throughout the city, reflecting one of the reasons why a large percentage of rooftop area is available for biosolar roof development. This unique design though, along with other locally significant architectural styles, is protected in special districts making any rooftop adjustments difficult. This status directly impacts the potential of biosolar roof development as the Flamingo Park Historic District and Ocean Beach Historic District, coincide directly with the area of most suitable rooftops in the south of the island. As a result, there is significant policy work and building assessments to be accomplished to balance both historical preservation and rooftop sustainability solutions. Suitable rooftops in the center of the island in residential areas could have an easier time adopting such solutions, especially given the existing city ordinances, city resolutions, and federal legislation supporting solar incentives and sustainable roof adjustments (Table 5). It should be considered, however, that the type of building is important for whether or not biosolar roofs are a good solution. For large roofs like the Miami Beach Convention Center, the biosolar potential may be high, but lighting structures on the roof of the building prevent added weight from being considered (Abuseif & Gou, 2018).

Interestingly, the main barrier for biosolar roof development is related to existing buildings only, given that city ordinances now require new construction of 7000 sq. ft. to automatically include sustainable roofing systems. This means that new buildings would likely already be suitable for biosolar roofs given a system like this would fit legal requirements. Analysis of existing building capacity for biosolar would be determined on a more case-by-case basis, revealing a limitation of this type of urban study (Slootweg, et al., 2023).

It should be acknowledged that limitations in data availability also resulted in conclusions based on the 2018 roofscape. Any new roofing systems that have been installed since would alter the multiple-criteria suitability analysis. Since the city ordinance requiring sustainable roofing systems in new construction of 7000 sq. ft. was passed in 2019, any new construction past this date would need to be accounted for. This is due to differences in green connectivity, solar energy production, and UHI mitigation which new roofing systems would impose.

Furthermore, since the methodology used in this thesis incorporates multiple different criteria, different weights can be used to prioritize different problems the city wishes to resolve. For example, if the city wishes to reduce the UHI Effect primarily, this layer could be weighed twice as important as green connectivity and solar energy production using the same model. A different output map would reveal which rooftops are most suitable for resolving these concerns. Inclusion of additional factors like stormwater management and air quality mitigation could also expand the model if appropriate data is available.

5.2 Biosolar rooftop suitability in other cities

While there does not exist a similar study conducted in South Florida, these results can be compared to the results of similar studies from other cities. Prominently, the city of Amsterdam in the Netherlands was studied for biosolar roof, green roof, and solar roof potential (Slootweg, et al., 2023). This study's methodology was pivotal for this thesis GIS methodology. The cities of Madrid, Spain, and Toronto, Canada, were also explored for their green roof potentials (Velázquez, et al., 2019; Jung, et al., 2025).

It is interesting to note similarities between the most suitable building types as Slootweg et al. found residential areas to be the least suitable in Amsterdam and industrial buildings to be most suitable for biosolar, green, and solar roofs, while the results from this study show that “residential” is also the least suitable building roof type for biosolar whereas “service & recreation” and “other” were the most suitable building roof types for biosolar (Figure 10). Biosolar potential, however, was noticeably less impactful in Amsterdam than in Miami Beach as greenery would only increase by 4.8% (compared to 11%) and electricity demand for residents would be 90% accounted for in Amsterdam (compared to 187-195% in Miami Beach) (Slootweg, et al., 2023). This shows the significant impact biosolar roof development can have in Miami Beach and how this can vary greatly depending on local factors.

A similar multi-criteria methodology was completed for rooftop potential in Madrid, but this was done for green roofs only and included different input variables (Velázquez, et al., 2019). In this 2019 study, pollution, traffic, and population were considered alongside a mutual variable with this thesis: green spaces. Nevertheless, green spaces were also measured differently as data for urban trees was included and a more complete connectivity analysis was completed using the GUIDOS tool from literature (Velázquez, et al., 2019). The results, however, proved that the connectivity of roofs selected by their model would be low despite having positive environmental benefits from the installation of new green roofs (Velázquez, et al., 2019). While connectivity was not quantitatively measured in this thesis, such a measurement could positively inform the research about the proposed suitability's effectiveness. Combining the approach of Velázquez et al. with the multi-criteria suitability analysis completed in this thesis could also address the limitations of the green connectivity analysis whereby only green spaces were included and urban tree canopy data availability limitations prevented a more holistic analysis.

While the policy analysis of this thesis revealed the feasibility of Miami Beach's biosolar potential, other qualitative research methods could also be considered for a more comprehensive assessment. This includes incorporation of citizen preferences as was completed in a green roof potential study about Toronto (Jung, et al., 2025). This is a significant research limitation which other GIS analyses also did not account for (Slootweg, et al., 2023; Velázquez, et al., 2019). Here, new geospatial factors, like flood regulation, and air quality improvement, were considered alongside mutual factors with the model presented in this thesis, including green connectivity and UHI mitigation (Jung, et al., 2025). The results of citizen preferences, moreover, were mapped quantitatively to create a prioritization scheme (Jung, et al., 2025). Utilization of such methodology could create a more interesting combined geospatial-socioeconomic study for Miami Beach. If a survey were created and results mapped alongside the results of this thesis, this could reveal public interest in rooftop sustainability solutions. This would be greatly beneficial towards further understanding the true potential of biosolar roof development in Miami Beach given most suitable roofs are residential, and require residents' invested interest.

5.3 Implications for biosolar roof research

Developing a methodology for cities to determine the potential of their roofscapes for biosolar and other sustainable rooftop solutions is vital for working towards local and global sustainability goals. This methodology can be reused by Miami Beach officials once more recent data becomes accessible by simply reusing the Python script for the GIS analysis. With a few adjustments, the same methodology can be applied to cities whose rooftop parameters are the same. Since rooftop parameters for biosolar roof development are less stringent than those for green roofs or solar roofs individually (Slootweg, et al., 2023), this GIS analysis should be reproducible across different climates. However, it is important to note that specific building information like load-bearing capacity, is vital towards understanding where biosolar roofs can be installed. This information is too specific for an urban potential study like this, however, and should be left to the discretion of architects and designers when looking at the implementation of such developments.

Further, it is important to note that biosolar roof technology is constantly advancing. As a result, implementation of biosolar roof solutions based on the potential map from this study and other studies would best be completed in phases to ensure the roofscape is updated accordingly with technology. Additionally, this study only explored biosolar roofs as extensive green roof-photovoltaic combinations and not intensive green roof-photovoltaic combinations. This is a limitation based on available literature on biosolar roofs, green roofs, and solar roofs. Since building load-bearing capacity was omitted for consideration, extensive green roofs (whose weight is less) were the ideal choice for deriving the maximum realistic potential estimate of biosolar roof development. This is similar to how biosolar roofs were considered for development in other studies (Slootweg, et al., 2023). While intensive green roof-photovoltaic combinations have been shown to mitigate the UHI Effect better than extensive green roof-photovoltaic systems, more research is needed on the topic to address this limitation (Chow, et al., 2019).

6. Conclusion

6.1 Main takeaways

This thesis study explored the potential of biosolar roof development in Miami Beach using a GIS analysis and a policy analysis. The results can best be used to inform local officials on the state of biosolar roof potential in Miami Beach, and provide a methodology for other urban environments to examine their roofscape potential for such solutions. The main takeaways of this research can be highlighted through each SRQ:

- 1. To what extent does the Miami Beach roofscape support biosolar roof development?**
 - ✓ Up to 63% of the Miami Beach roofscape is suitable for biosolar roof development.
- 2. To what extent would biosolar roof development contribute to urban greenery in Miami Beach?**
 - ✓ If the entire potential for biosolar roof development in Miami Beach were reached, 50% more greenery (11% of the land cover) could be added to the city landscape.
- 3. To what extent would biosolar roof development reduce energy demand in Miami Beach?**
 - ✓ If the entire potential for biosolar roof development in Miami Beach were reached, almost twice (195%) the current energy demand could be satisfied via biosolar energy production.
- 4. To what extent does the Miami Beach roofscape support biosolar roof development in terms of green connectivity, solar energy output, and UHI mitigation?**
 - ✓ In consideration of green connectivity, solar energy output, and UHI mitigation benefits, biosolar roof development potential is (i) highest around the southern side of the island, and (ii) the majority (95%) of suitable rooftops are moderately to highly favorable to incur optimal benefits from these criteria.
- 5. To what extent does Miami Beach policy support biosolar roof development?**
 - ✓ The largest barrier to biosolar roof development in Miami Beach is the overlap between historical districts and suitable rooftops;
 - ✓ Current policy positively requires new construction to install sustainable roofing systems like biosolar;
 - ✓ There exists a significant amount of policy incentivizing biosolar roof development, however, the decision to implement biosolar in already-existing building rooftops remains mostly at the discretion of building owners.

Based on the results underpinning each SRQ, the potential of biosolar roof development in Miami Beach can be categorized in terms of geospatial/physical potential and feasibility. The former proves rooftop suitability in Miami Beach is generally high (63%), and most of these suitable roofs would support increased green connectivity, solar energy output, and UHI mitigation. The latter proves that biosolar roofs are (i) extremely feasible for new construction given sustainable roofing practices are now required, yet there remains (ii) challenges for existing construction given the historic-protected status for many Miami Beach buildings with suitable rooftops.

6.2 Scientific recommendations

Biosolar roof development is an emerging research field and will require more in-depth studies to increase accuracy and knowledge about the topic. Based on the information presented in this study, there are various recommendations for projects which could expand this type of work including reproducing similar studies with updated data, upgraded models, additional calculations, and supplemental considerations.

Firstly, many of the limitations of this study centered data availability concerns. To provide a more accurate green connectivity analysis, satellite imagery or urban tree canopy data would be necessary. Following this, a more structured connectivity analysis would provide more accurate results and understanding about the urban study area's greenery situation. With this adjustment, the rest of the methodology should remain similar and provide a multi-criteria suitability analysis with a more comprehensive outlook. If completed in the same study area, this could reveal how accurate the current model is in assessing biosolar rooftop suitability, and specifically from a green connectivity perspective. If completed in another study area, this future study could add to the literature of biosolar roof development potential across different cities and climates. If expanded further, this could also contribute more information on the importance of species ecology on biosolar roof development. This is a topic where more research is desperately needed.

Inclusion of improved and/or different models could also inform different methodologies for determining the potential of biosolar roofs in urban environments. Using the same methodology for the multi-criteria suitability analysis conducted in this study, factors such as stormwater management and air quality mitigation can be considered. This would require appropriate additional data and would create a more holistic understanding of these roofs' impact on cities. It could also be interesting to explore the combination of this model with the model presented in the research of Slootweg et al. (2023) whereby green roofs, solar roofs, and the competition between the two rooftop solutions were also considered. If completed in the same study area, this would contribute more understanding to biosolar roof development potential in different climates. If completed in another study area, this could add to under-studied knowledge gaps in biosolar roof development.

Furthermore, this study explored a few calculations for urban greenery and solar energy production to answer some of the SRQs. This could be expanded further to include cost-benefit analyses and the potential economic impact of biosolar roof development. Such information would be valuable towards understanding the true feasibility of such a project. In practice, this would include using the same model from this study and simply calculating values based on market trends, current policy, and previous literature. Regardless of which study area is selected for this future study, this could provide benefits to local decision makers and strengthen the multi-criteria suitability analysis model presented.

Lastly, one of the greatest limitations of this research is its urban perspective. While a study of this size struggles to consider building-specific requirements, a model which could incorporate load-bearing capacity as a factor for rooftop suitability would be ideal. This would provide the most accurate assessment of an urban roofoverlay's potential for biosolar, or any rooftop solution. It is highly recommended that further research continue here to provide a model which can be used by urban planners and architects alike.

6.3 Societal recommendations

Given the focus of this thesis was about biosolar roof development in Miami Beach, there are several recommendations for local officials to expand on the results of this study. These include reproducing the methodology with updated data, gathering citizen perspectives on the solution, examining the impact of biosolar roof development on spatial equity and social justice, and further exploring the feasibility of biosolar roof solutions in coastal island environments.

Given the results of this methodology are particularly useful for local officials and experts in Miami Beach and the lidar dataset used is from 2018, it should be reproduced with more updated data. This can be done using the Python script from this thesis. This would allow the potential of the urban roofscape to reflect contemporary standards, especially after the adoption of city ordinances supporting sustainable roofing systems. Potential future research could include exploring the impact of city ordinances on biosolar rooftop suitability in Miami Beach, general changes in suitability over time, and how the criteria from the multi-criteria suitability analysis have been impacted by new development.

It is also valuable to consider the preferences and perspectives of local citizens regarding the implementation of biosolar roofs and other sustainable roofing systems. While studies like these provide useful knowledge regarding the potential of such solutions in urban environments, research which considers citizen outlooks on such solutions inquires the solutions' true feasibility. Further, since residential rooftops proved to be the largest proportion of suitable rooftops from this study, asking residents about their preferences is vitally important given their decision-making power.

Social justice and spatial equity are additional points of future research recommended for local officials. Given the importance of spatial distribution of green spaces, generally, implementation of rooftop solutions like biosolar roofs will require understanding of socio-economic inequalities in the study area. This means that biosolar roofs should not only be installed in building rooftops where more affluent communities reside, as this will seclude biosolar benefits from many urban residents. If implemented with this understanding, biosolar roofs have the potential to further connect residential communities. If this is not considered, the opposite becomes true.

Another item of research which was not explored thoroughly in this study includes biosolar roof feasibility in coastal island environments. While this would involve a more technical study on the impact of factors like proximity to ocean water, the results would dramatically improve understanding of biosolar roofs relevant to this thesis. Similar to the scientific recommendation for consideration of load-bearing capacity in this thesis model, consideration of the results of this proposed research could result in more accurate calculations and potential assessments.

6.4 Final considerations

This research provides several opportunities for advancing local sustainable development in Miami Beach and biosolar roof research internationally. It is my hope that this study can be used for local officials and scientific researchers alike. To see and use the full Python script for the GIS analysis presented here, please visit GitHub online (<https://github.com/thiagoesslinger>).

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Appendix

A. Datasets

Here, the datasets used for the GIS analysis are described in greater detail for reproducibility.

Table 8. Datasets information

Dataset	Parameters
2018 Miami-Dade County ITD Lidar: Miami-Dade County, FL (fl2018_miamidade_Job1163512)	Source: NOAA Data Access Viewer Projection: State Plane 1983, Zone: Zone 0901 Florida East, Horizontal Datum: NAD83, Horizontal Units: Meters, Vertical Datum: NAVD88, Vertical Units: Meters, File Format: Tiff 32-bit Float, Bin Method: Average, Bin Size: 0.5, Bin Units: Meters, Data Classification: Building, Data Returns: Any Points, Ancillary Data: No Ancillary Data, Geoid Name: GEOID18
Land_Use	Source: MDC Open Data Hub Initial projected coordinate system: WGS_1984_Web_Mercator_Auxiliary_Sphere Projection: Mercator_Auxiliary_Sphere
Miami Beach Municipal Boundary	Source: MDC Open Data Hub Initial projected coordinate system: WGS_1984_Web_Mercator_Auxiliary_Sphere Projection: Mercator_Auxiliary_Sphere
Solar Azimuth and Solar Altitude values from NOAA Solar Position Calculator	Source: NOAA Earth System Research Lab City: Miami, FL Lat Deg: 25 Lat Min: 46 Lat Sec: 1 Long Deg: 80 Long Min: 10 Long Sec: 59
Trust for Public Land UHI Severity for U.S. cities - 2019	Electronic source: ArcGIS Pro Online Data collection source: Landsat 8 imagery band 10 (ground-level thermal sensor) Raster cell size: 30 x 30 m

B. ArcGIS Pro parameters and models

B0. Pre-processing parameters

Prior to usage of the datasets described in Appendix A, pre-processing was required to ensure that the proper parameters were selected. This included merging of lidar files, clipping to the Miami Beach geographic boundaries, and redefining land use data so that it was consistent with this focus of this thesis. A full description of each tool used for this purpose is described below in Table 9.

Table 9. ArcGIS Pro tool parameters used in pre-processing data.

Tool	Parameters
Mosaic to New Raster	Input rasters: <i>Job1163512_004_002.tif, Job1163512_004_001.tif, Job1163512_003_002.tif, Job1163512_003_001.tif, Job1163512_002_002.tif, Job1163512_002_001.tif, Job1163512_001_002.tif, Job1163512_001_001.tif</i> Spatial reference for raster: <i>NAD_1983_2011_StatePlane_Florida_East_FIPS_0901 / VCS:NAVD_1988</i> Pixel type: <i>32 bit float</i> Number of bands: <i>1</i> Mosaic operator: <i>Last</i> Mosaic colormap mode: <i>First</i>
Clip Raster	Input raster: <i>Lidar building mosaic</i> Output extent: <i>Miami Beach municipal boundary</i> Use input features for clipping geometry
Calculate Field	Input: <i>Land_Use</i> Code block: <pre>def redefine_LU(value): if value in {10,11,12,13,20,30,35,69,180}: return 1 #residential elif value in {101,110,113,160,170,200}: return 2 #commercial elif value in {320,630,632,635,636}: return 3 #industrial elif value in {411,412,414,420,430,435,440,450,470,517,530}: return 4 #recreation & services elif value == 640: return 6 #roads else: return 5 #other</pre>

B1. Rooftop suitability analysis model

The model used to calculate rooftops with slopes of 10° or less and a total area of 10 m² or more is described in this section. All calculations were completed on ArcGIS Pro. Each process shown in the figure is described in greater detail in the subsequent table. This model was based on the methodology of Slootweg et al. (2023) and was adjusted as necessary.

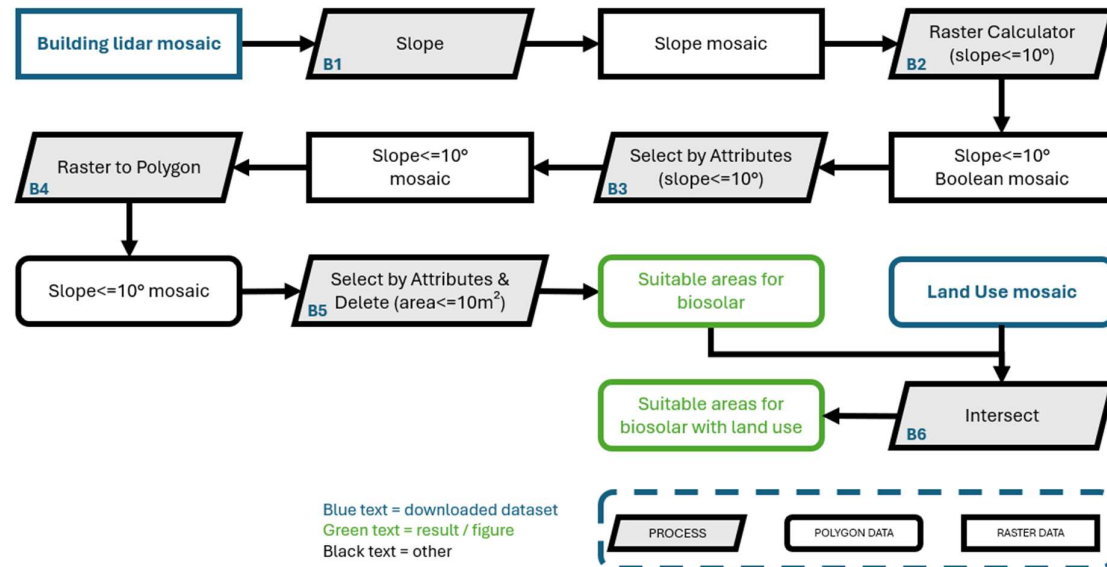


Figure 17. Expanded GPM for rooftop suitability analysis.

Table 10. ArcGIS Pro tool parameters used based on Figure 17.

Label	Tool	Parameters
B1	Slope	Input raster: <i>Lidar building mosaic</i> Output raster: <i>Slope</i> Output measurement: <i>Degree</i> Method: <i>Planar</i> Z factor: <i>1</i> Target device for analysis: <i>GPU then CPU</i>
B2	Raster Calculator	"Slope <= 10"
B3	Select by Attributes	Selected slopes under 10° only
B4	Raster to Polygon	Input raster: <i>Slopes under 10°</i> Field: <i>Value</i>
B5	Select by Attributes	Deleted all polygons with Shape_Area < 10 m ²
B6	Intersect	Input features: <i>Polygon of slopes under 10° and area greater than or equal to 10 m², land use data</i> Attributes to Join: <i>All attributes</i> Output Type: <i>Same as input</i>

B2. Green connectivity analysis model

The model used to find where green spaces are closest to suitable roofs is described in this section. All calculations were completed on ArcGIS Pro. Each process shown in the figure is described in greater detail in the subsequent table.

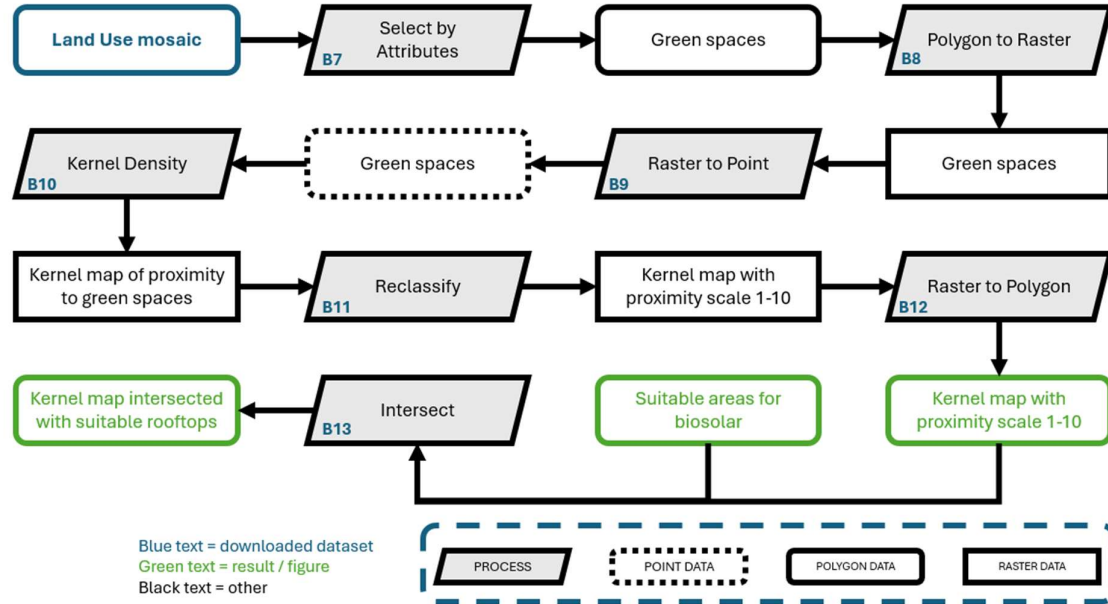


Figure 18. GPM for Green connectivity analysis.

Table 11. ArcGIS Pro tool parameters used based on Figure 18.

Label	Tool	Parameters
B7	Select by Attributes	Selected land use of classification based on Table 23
B8	Polygon to Raster	Input features: <i>Green spaces polygon</i> Value field: <i>LU code</i> Cell assignment type: <i>Cell center</i> Priority field: <i>NONE</i> Cellsize: <i>0.5</i> <i>Build raster attribute table</i>
B9	Raster to Point	Input raster: <i>Green spaces raster</i>
B10	Kernel Density	Input polyline feature: <i>Green spaces as polyline</i> Population field: <i>NONE</i> Output cell size: <i>0.5</i> Search radius: <i>300 m</i> Area units: <i>square kilometers</i> Output cell values: <i>Densities</i> Method: <i>Planar</i>
B11	Reclassify	Input raster: <i>Kernel map</i> Reclassification: <i>1-10 based on closeness to green spaces</i>
B12	Raster to Polygon	Input raster: <i>Reclassified Kernel map</i> Field: <i>Value</i> <i>Create multipart features</i>
B13	Intersect	Input features: <i>Reclassified Kernel map, suitable rooftops</i> Attributes to join: <i>All attributes</i> Output type: <i>Same as input</i>

B3. Shadow analysis model

The model used to calculate shading of rooftops throughout the year is described in this section. All calculations were completed on ArcGIS Pro and Microsoft Excel. Each process shown in the figure is described in greater detail in the subsequent table. This model is based on the methodology of Hong et al. 2017 and was adjusted as necessary.

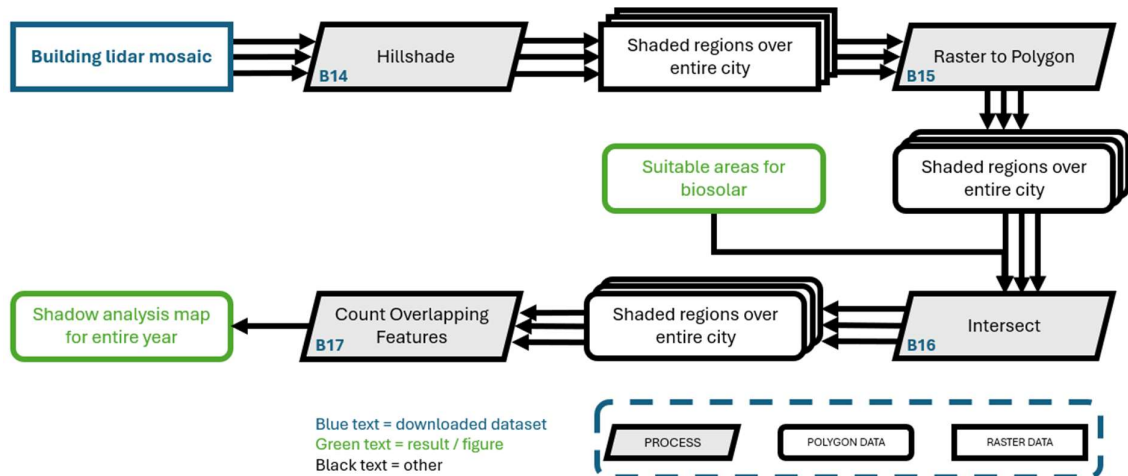


Figure 19. GPM for Shadow analysis.

Table 12. ArcGIS Pro tool parameters used based on Figure 19.

Label	Tool	Parameters
B14	Hillshade	Input raster: <i>Building Lidar mosaic</i> Azimuth & Altitude values were input as calculated by NOAA Solar Position Calculator for each hour-month combination <i>Model shadows</i> Z factor: 1
B15	Raster to Polygon	Input rasters: <i>Hillshade results</i>
B16	Intersect	Attributes to join: <i>All attributes</i> Output type: <i>Same as input</i>
B17	Count Overlapping Features	Input features: <i>Hillshade results as polygons</i> Minimum overlap count: 0

B4. UHI analysis model

The model used to find where the UHI Effect was greatest over suitable rooftops is described in this section. All calculations were completed on ArcGIS Pro. Each process shown in the figure is described in greater detail in the subsequent table.

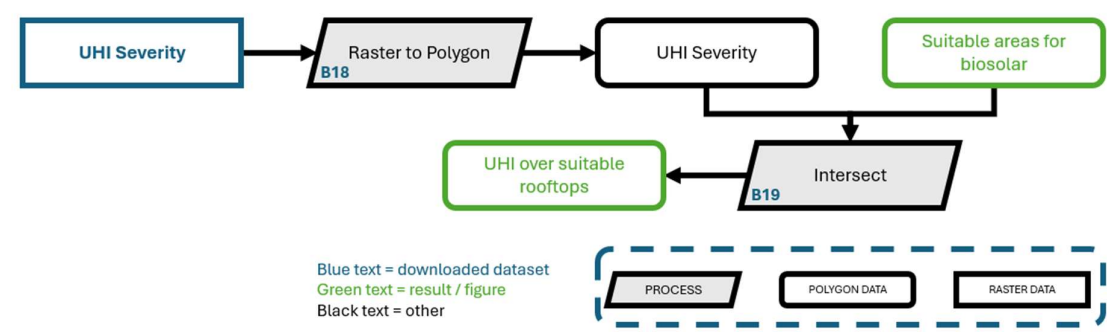


Figure 20. GPM for UHI analysis.

Table 13. ArcGIS Pro tool parameters used based on Figure 20.

Label	Tool	Parameters
B18	Raster to Polygon	Input raster: <i>UHI severity</i>
B19	Intersect	Input features: <i>UHI severity, suitable rooftops</i> Attributes to join: <i>All attributes</i> Output type: <i>Same as input</i>

B5. Multiple-criteria suitability analysis model

The model used to calculate which roofs are most suitable for biosolar roof development based on the previous analyses is described in this section. All calculations were completed on ArcGIS Pro. Each process shown in the figure is described in greater detail in the subsequent table.

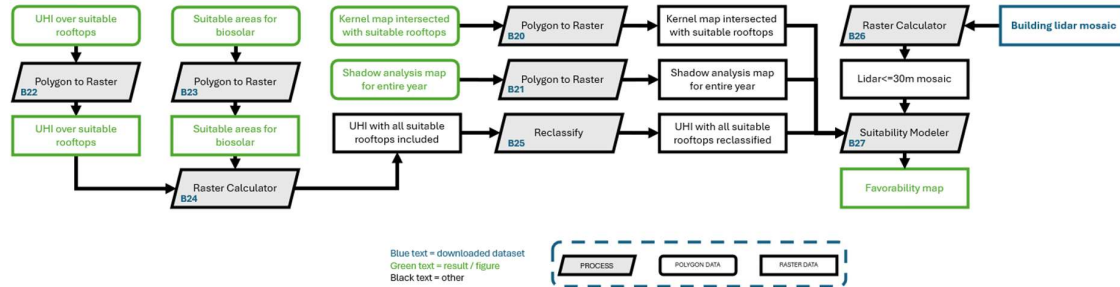


Figure 21. GPM for multiple-criteria suitability analysis.

Table 14. ArcGIS Pro tool parameters used based on Figure 21.

Label	Tool	Parameters
B20	Polygon to Raster	Input features: <i>Kernel map for green connectivity</i> Value field: <i>Value</i> Cell assignment type: <i>Cell center</i> Priority field: <i>NONE</i> Cellsize: <i>0.5</i> <i>Build raster attribute table</i>
B21	Polygon to Raster	Input features: <i>Shadow analysis map</i> Value field: <i>Value</i> Cell assignment type: <i>Cell center</i> Priority field: <i>NONE</i> Cellsize: <i>0.5</i> <i>Build raster attribute table</i>
B22	Polygon to Raster	Input features: <i>UHI-suitable roof intersect polygon</i> Value field: <i>ID</i> Cell assignment type: <i>Cell center</i> Priority field: <i>NONE</i> Cellsize: <i>0.5</i> <i>Build raster attribute table</i>
B23	Polygon to Raster	Input features: <i>Suitable rooftops polygon</i> Value field: <i>ID</i> Cell assignment type: <i>Cell center</i> Priority field: <i>NONE</i> Cellsize: <i>0.5</i> <i>Build raster attribute table</i>
B24	Raster Calculator	<i>"UHI-suitable roof intersect + Suitable rooftops"</i>
B25	Reclassify	Input raster: <i>UHI-suitable roof intersect raster</i> Reclassification: <i>0-10 based on 1-5 severity scale and 0 (suitable roofs without UHI severity index label)</i>
B26	Raster Calculator	<i>"Lidar <= 30"</i>
B27	Suitability Modeler	Model input type: <i>Criteria</i> Set suitability scale: <i>1 to 10</i> Weight by: <i>Multiplier</i> Input rasters: <i>Shadow analysis map, UHI severity map, Green connectivity Kernel map</i> Transformations: <i>1 (non-suitable) to 10 (suitable) for each raster</i>

In order to ensure a successful favorability map based on the Suitability Modeler tool, rooftops that were not suitable were set as a restriction as a precautionary measure. Rooftops with heights greater than 30 m were also set as a restriction based on the original lidar dataset. Furthermore, the following transformations were completed for each input raster. The option was selected to create equal spacing between values for assigning the favorability value. The only exception is for the UHI analysis whereby the values 1-5 in heat stress were assigned higher favorability and the areas without any recoded heat stress were assigned lowest favorability on an uneven scale. This was done to ensure that areas of high heat stress were preferentially selected in the model as even spacing would not have shown a fair assessment for UHI consideration.

Table 15. Transformation of green connectivity analysis map on Suitability Modeler tool.

Class	Value	Suitability
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10

Table 16. Transformation of shadow analysis map on Suitability Modeler tool.

Class	Start value	End value	Suitability
1	0	14.4	10
2	14.4	28.8	9
3	28.8	43.2	8
4	43.2	57.6	7
5	57.6	72	6
6	72	86.4	5
7	86.4	100.8	4
8	100.8	115.2	3
9	115.2	129.6	2
10	129.6	144	1

Table 17. Transformation of UHI analysis map on Suitability Modeler tool.

Class	Value	Suitability
1	5	10
2	4	9
3	3	8
4	2	7
5	1	6
6	0	1

C. Land use classifications

Table 18. Explanation of “residential” land use classification.

LU Code	Description
10	Single-Family, Med.-Density (2-5 DU/Gross Acre)
11	Single-Family, High Density (Over 5 DU/Gross Acre, other than Townhouses, Duplexes and Mobile Homes)
12	Townhouses
13	Single-Family, Low-Density (Under 2 DU/Gross Acre)
20	Two-Family (Duplexes)
30	Multi-Family, Low-Density (Under 25 DU/Gross Acre)
35	Multi-Family, High Density (Over 25 DU/Gross Acre)
69	Residential MF-- government-owned or government subsidized multi-family residential or elderly housing
180	Residential predominantly (condominium/ rental apartments with lower floors Office and/or Retail. High density > 15 dwelling units per ac, multi-story buildings (Generally more than 5 stories)

Table 19. Explanation of “commercial” land use classification.

LU Code	Description
101	Shopping Centers (Regional and Community)
110	Sales and Services (Wholesale facilities, Spot commercial, strip commercial, neighborhood shopping centers/plazas). Excludes office facilities
113	Office Building
160	Office/Business/Hotel/Residential. Substantial components of each use present, Treated as any combination of the mentioned uses with a hotel as part of development
170	Office and/or Business and other services (ground level) / Residential (upper levels). Low-density < 15 dwellings per acre or 4 floors
200	TRANSIENT-RESIDENTIAL (HOTEL-MOTEL)

Table 20. Explanation of “industrial” land use classification.

LU Code	Description
320	Industrial Intensive, heavy-light manufacturing, and warehousing-storage type of use
630	Electric Power (Generator and Substation, and Service Yards)
632	Oil and Gas Storage (Tank Farms)
635	Water Supply Plants
636	Sewerage Treatment Plants

Table 21. Explanation of “service & recreation” land use classification.

LU Code	Description
411	Public Schools, Including Playgrounds (K-12, Vocational Ed., Day Care and Child Nurseries)
412	Private Schools, Including Playgrounds (K-12, Vocational Ed., Day Care and Child Nurseries)
414	Colleges and Universities, Including Research Centers, Public and Private
420	Cultural (auditoriums, convention centers, exhibition centers, museums, art galleries, libraries)
430	Hospitals, clinics, medical offices and/or dental facilities
435	Nursing homes, Assisted living facilities, and Adult congregate living quarters
440	Houses of Worship and Religious, and associated uses (parking, retreat houses, residencies, childcare, etc.)
450	Governmental/Public Administration (Other than Military or Penal)
470	Social Services, and Charitable institutions (Shrines, Elks, Moose, Lions Club)
517	Private Recreational Facilities Associated with private Residential Developments, except marinas/yacht basins, includes landscape and open spaces associated to residential, commercial and office developments
530	Golf courses, Public and Private

Table 22. Explanation of “other” land use classification

LU Code	Description
112	Marine commercial (includes private commercial [non-recreational] marinas and repair yards on public or private land)
451	Military Facilities
510	Municipal Operated Parks
519	Beaches
527	Marina complexes (docks, piers, moorings, ramps, boat lifts and hoists, boat maintenance and repair, boat storage, fueling operations) for recreational craft located within Parks and Preserves and other small craft harbor complexes used primarily for rec
550	County Operated Parks
580	Other Nature Preserves and Protected Areas (State Mangrove Preserves, Turkey Point Wilderness Area, Great Cypress Swamp Preserves, and acquired government owned EEL sites)
612	Ocean Ship Terminals and Port Facilities, Bay and River Based
613	Bus/Truck/Freight Forwarding Terminals
633	Communications (Radio, TV, Cable, and Phone), excluding Antenna Arrays
640	Streets and Roads, except Expressways and Private Drives
642	Private Drives
645	Highways and Expressways right-of-way and associated open and landscaped areas excluding paved expressways and ramps
646	Street right-of-way and entrance features both public and private, and utility easements
650	Parking - Public and Private Garages and Lots
801	Vacant Government owned or controlled
803	Vacant, Protected, Government-Owned or controlled. EEL sites included
804	Vacant, Non-Protected, Privately-Owned
805	Major Approved Projects
918	Inland water bodies (Lakes, Watercourses) associated with residential developments
932	Coastal Water (Bay only) within the Biscayne Bay Urban Aquatic Preserve (Excluding Ocean Waters)
935	Remaining Bay Waters (Excluding Ocean)

Table 23. Explanation of "green space" land use classification.

LU Code	Description
510	Municipal Operated Parks
519	Beaches
530	Golf courses, Public and Private
550	County Operated Parks
580	Other Nature Preserves and Protected Areas (State Mangrove Preserves, Turkey Point Wilderness Area, Great Cypress Swamp Preserves, and acquired government owned EEL sites)

D. Solar azimuth and elevation values

Table 24. Solar azimuth values for Miami, FL, for the 15th day of each month.

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan	106.31	112.14	119.03	127.59	138.6	152.85	170.4	189.46	207.04	221.33	232.38	240.96	247.88	253.73	Dark
Feb	97.81	104.05	111.05	119.6	130.79	146.09	166.47	189.83	210.98	227.11	238.88	247.79	255.02	261.37	Dark
Mar	Dark	88.63	95.16	102.15	110.54	121.8	138.65	164.43	196	221.69	238.47	249.71	258.08	265.09	271.65
Apr	71.94	78.89	85.22	91.63	98.98	108.98	126	161.84	212.23	240.6	254.66	263.58	270.54	276.86	283.33
May	64.42	71.12	76.94	82.4	88.08	95.07	107.01	148.98	237.75	259.33	268.29	274.52	280.02	285.58	291.73
Jun	60.11	66.72	72.28	77.19	81.82	86.68	93.2	115.68	256.54	269.08	274.81	279.53	284.2	289.26	295.08
Jul	60.99	67.81	73.58	78.77	83.84	89.47	97.71	123.8	242.12	263.41	271.14	276.65	281.7	286.93	292.79
Aug	67.67	74.69	80.89	86.92	93.52	102.09	116.58	152.32	216.18	246.42	259.41	267.5	273.93	279.93	286.2
Sep	78.74	85.6	92.14	99.14	107.61	119.4	138.36	169.88	206.59	231.73	246.62	256.51	264.11	270.77	277.34
Oct	Dark	97.04	103.67	111.29	120.91	134.04	152.68	177.18	202.44	222.42	236.53	246.73	254.66	261.4	267.74
Nov	106.26	112.61	120.2	129.79	142.34	158.66	178.19	198.03	215.01	228.17	238.19	246.05	252.55	Dark	Dark
Dec	109.7	115.61	122.75	131.72	143.23	157.83	175.15	193.19	209.38	222.5	232.72	240.75	247.25	Dark	Dark

Table 25. Solar elevation values for Miami, FL, for the 15th day of each month.

	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan	-15.44	-2.58	9.57	20.83	30.7	38.34	42.64	42.66	38.41	30.79	20.94	9.7	-2.45	-15.31	Dark
Feb	-13.17	0.55	13.03	25.22	36.27	45.29	50.79	51.24	46.5	37.95	27.16	15.12	2.53	-10.92	Dark
Mar	Dark	-7.53	6.07	19.33	32.28	44.43	54.8	61.37	61.33	54.72	44.31	32.17	19.21	5.96	-7.63
Apr	-13.41	0.18	13.09	26.56	40	53.12	65.16	73.41	71.64	61.67	49.16	35.91	22.44	9.03	-4.28
May	-8.04	4.61	17.47	30.74	44.19	57.68	70.95	82.14	77.99	65.32	51.9	38.41	25.03	11.91	-0.61
Jun	-6.55	5.63	18.18	31.19	44.46	57.88	71.38	84.58	80.86	67.45	53.97	40.58	27.38	14.47	2.19
Jul	-8.61	3.74	16.34	29.42	42.76	56.23	69.7	82.5	81.24	68.24	54.75	41.29	27.97	14.91	2.42
Aug	-12.24	0.93	13.77	27.16	40.65	54.02	66.78	76.75	75.59	64.8	51.86	38.45	24.96	11.59	-1.45
Sep	-15.67	-2.17	11.26	24.65	37.77	50.16	60.73	66.77	64.74	56.07	44.42	31.6	18.3	4.92	-8.69
Oct	Dark	-5.12	8.21	21.02	33.13	43.87	51.98	55.53	53.17	45.84	35.53	23.64	10.92	-2.24	-15.81
Nov	-9.05	3.85	15.8	26.85	36.23	42.91	45.64	43.7	37.62	28.62	17.8	5.94	-6.79	Dark	Dark
Dec	-13.21	-0.34	11.1	21.83	30.96	37.64	40.81	39.82	34.88	26.93	16.95	5.74	-6.5	Dark	Dark

E. Building shadow analysis

Table 26. Biosolar potential overlap with unshaded area during daylight hours. Daylight Savings Time is considered.

	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
JANUARY			66%	84%	90%	92%	93%	93%	92%	89%	83%	66%			
FEBRUARY		4%	75%	87%	92%	94%	95%	94%	94%	92%	88%	78%	29%		
MARCH			54%	84%	91%	95%	96%	97%	97%	96%	94%	90%	83%	55%	
APRIL		2%	76%	89%	94%	96%	98%	99%	98%	97%	95%	92%	87%	67%	
MAY		42%	81%	91%	95%	97%	99%	99%	99%	98%	96%	93%	88%	73%	
JUNE		48%	82%	91%	95%	97%	99%	99%	99%	98%	96%	94%	89%	78%	27%
JULY		35%	80%	90%	95%	97%	98%	99%	99%	98%	97%	94%	89%	78%	29%
AUGUST		8%	77%	89%	94%	97%	98%	99%	99%	98%	96%	93%	88%	74%	
SEPTEMBER			73%	88%	93%	96%	97%	98%	98%	96%	94%	90%	83%		
OCTOBER			62%	85%	91%	94%	95%	96%	96%	94%	91%	86%	71%		
NOVEMBER		36%	79%	88%	91%	93%	94%	93%	92%	88%	81%	52%			
DECEMBER			70%	85%	90%	92%	93%	92%	91%	87%	80%	50%			

F. Interview questions

The following questions were sent to interviewees before the interview date. During the interview, they were used to guide information-seeking.

1. What plans does the City of Miami Beach already have in place for rooftop solar? Green roofs? Biosolar roofs?
2. Has biosolar roof development already been explored for the City of Miami Beach? If so, what was the outcome?
3. What does urban planning in the City of Miami Beach look like? How does sustainability already play a role in decision making?
4. Are there sustainable building regulations in place for the City of Miami Beach? How does this apply to existing and new developments?
5. What is the relationship between sustainability policy locally, county-wide, state-wide, and nationally?

G. Interview ATLAS.ti transcript analysis

The following information was derived from interviews with Miami Beach officials. The actual transcript is not made publicly available. Sources are based on Table 1.

Table 27. Interview results related to SRQ1.

Theme	Relevant information	Source(s)
Aesthetics	Aesthetics is significant in Miami Beach, and some of the challenges to biosolar implementation include: • Potential unattractiveness feature • Protected status of historical buildings	1,2
Equity	Social sustainability is also an important consideration for implementation of biosolar roofs. Some equity-related challenges include: • Different rooftop parameters based on socio-economic status of property owners • Luxury versus affordable rooftop solutions • Rooftop solar does not help renters and lower-income residents	1
Technical	Feasibility of biosolar roof development depends on many technical considerations this thesis may or may not already consider. Some of these considerations include: • Most Miami Beach roofs don't have angles, so potential should be large • Air conditioning units on rooftops will be a large obstruction to rooftop usage • Impact of salt spray on biosolar roofs needs to be explored further • Structural capacity of buildings is extra important due to old age of many Miami Beach buildings • The payout period for solar is currently too large to justify from the government perspective	1,2,3

Table 28. Interview results related to SRQ2-3.

Theme	Relevant information	Source(s)
Biosolar benefits	The following was discussed as the potential positive impact of biosolar roof development: • Miami Beach UHI can be mitigated through cooling effect	1,2
Greenery benefits	The following was discussed as a relevant example for the potential positive impact of increased greenery from biosolar roof development: • Rooftop bars in the City of Miami already add greenery for increased comfort	2
Solar benefits	The following was discussed as benefits of rooftop solar that biosolar roofs, too, could provide: • Rooftop solar as distributed generation (not power generation) is part of the energy transition	2

Table 29. Interview results related to SRQ5.

Theme	Relevant information	Source(s)
Ideal policy	All interviewees expressed visions for what the ideal policy would look like to support biosolar roofs and similar initiatives in Miami Beach: • Symbiotic solutions that support the environment, lower prices, and cool temperatures • Painting of roofs with lighter colors is also important	1,2,3
Existing policy	Many programs and policies already in place were also discussed as relevant to biosolar roofs: • Net metering and federal tax incentives exist for residential rooftop solar • Resilience code for new construction to withstand sea-level rise and other storms • UHI Ordinance requires all new construction to have sustainable roofs • Green Building Ordinance requires new construction over 7000 ft. to be LEED-certified or Living Building Challenge-certified • Energy Efficiency Community Block Grant provides federal funding for local projects • BE 305 Program is examining energy efficiency in Miami Beach Convention Center	1,2,3
Proposed policy	Discussion of proposed policy was informative about ongoing projects in Miami Beach. The following was relevant to biosolar roof development: • Significant work on electricity decarbonization and renewable incentives • Rooftop solar has been proposed for Miami Beach Fleet	1,3
Governance	Understanding of governance structures was of paramount importance to the feasibility of biosolar roof development. The following was discussed: • Resilient 305 group meets monthly with other 100 resilient cities listed from Bloomberg Foundation • Southeast Florida Compact meets monthly to share resources • USDN and its subgroups meet to share resources between cities	3
Local context	The Miami Beach context is unique, and thus it is important to frame biosolar roof development from this perspective. The following is important to consider: • Financial burden ○ Cost of electricity in Florida is cheap, creating a barrier for solar adoption ○ Cost of feasibility studies are too expensive ○ New solutions will cost time and money due to adjustment period • Behavioral change ○ Fear of early adoption / new technologies has prevented significant development ○ Balance between short-term vs. long-term thinking ○ Balance between individual vs. group responsibility for sustainable solutions	2,3
Political atmosphere	The adoption of environmental policy is dependent on the political atmosphere of the area. The following was discussed as relevant to the adoption of biosolar roofs: • Differences between federal, state, county, and city environmental agendas • Demographic shifts in southeast Florida causing subsequent political shifts • Large expenditures require large paybacks to be considered	1,2,3